Evaluating surface ozone-temperature relationships over the eastern U.S. in chemistry-climate models

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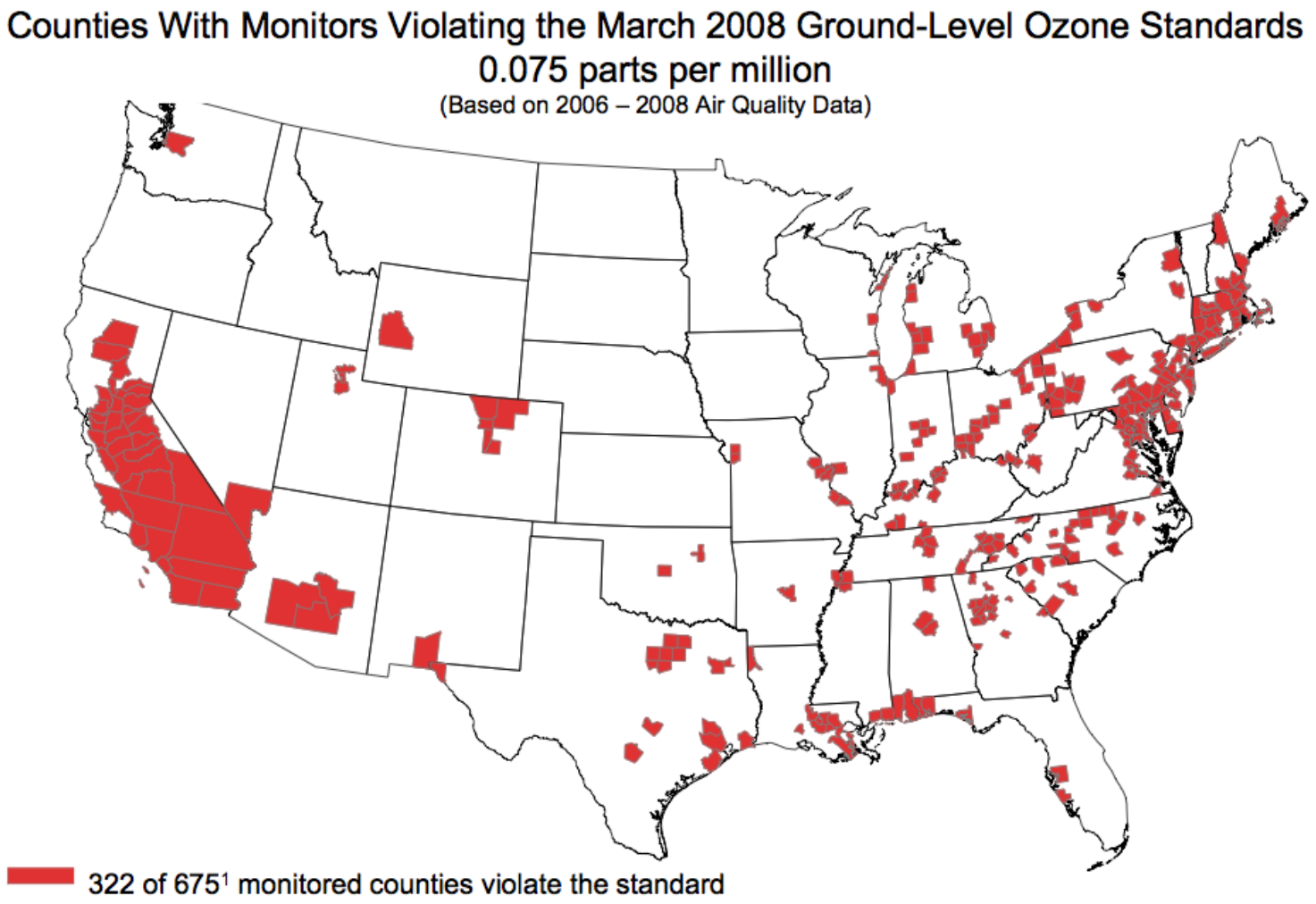
A GFDL Lunchtime Seminar

August 17th, 2011

The U.S. O_3 problem: over 150 million people breathe air deemed unhealthy by EPA



About 1 in 2 people in the U.S. live in these areas **[*EPA*, 2010]**

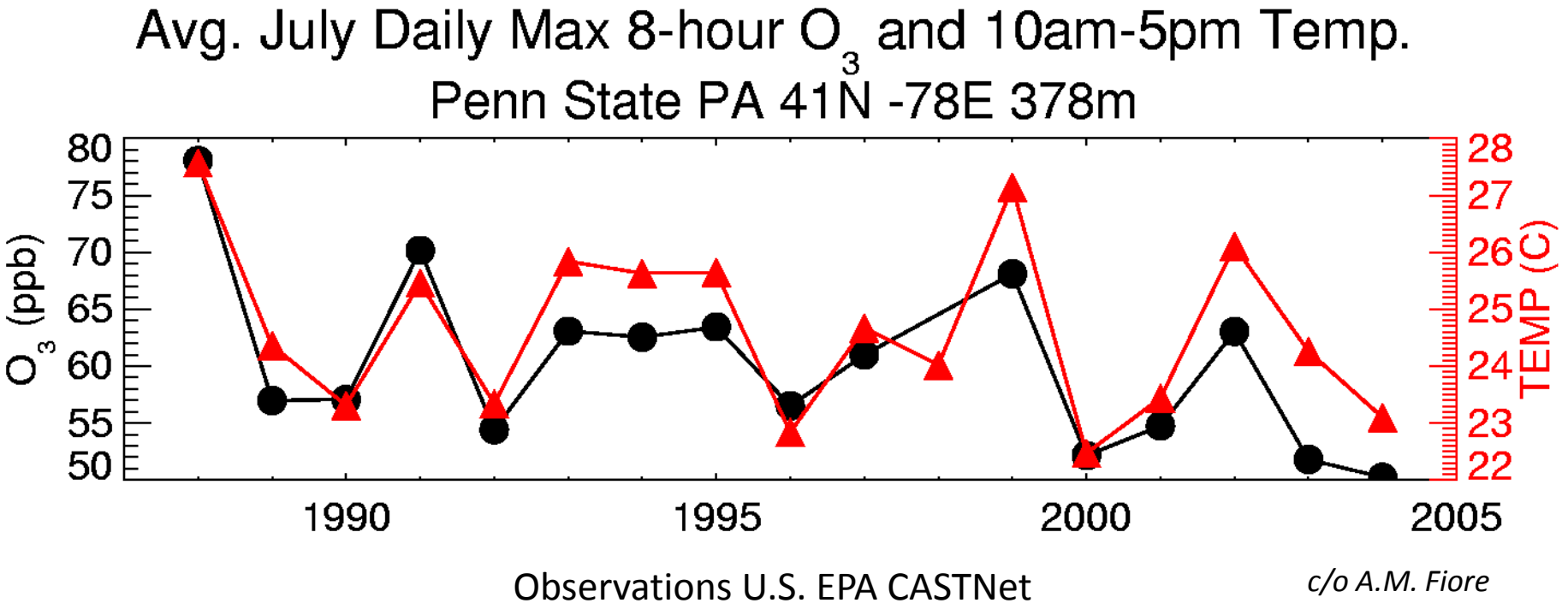
(*) To attain this standard:
the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentrations measured at each monitor within an area over each year must not exceed 0.075 ppm. (effective May 27, 2008)

Presentation Outline

- Implications for air quality response to climate change
- Characterizing the O_3-temperature relationship over the eastern US
- How well does a chemistry-climate model represent this relationship, particularly in light of a modeled summertime O_3 bias over this region?
- Do biases in surface temperature contribute to this modeled O_3 bias?

Surface O_3 varies strongly with temperature

Observational studies have shown strong correlation between surface temperature and O_3 concentrations (Bloomer et al., 2009; Camalier et al., 2007; Cardelino and Chameides, 1990; Clark and Karl, 1982; Korsog and Wolff, 1991)



Observations U.S. EPA CASTNet

c/o A.M. Fiore

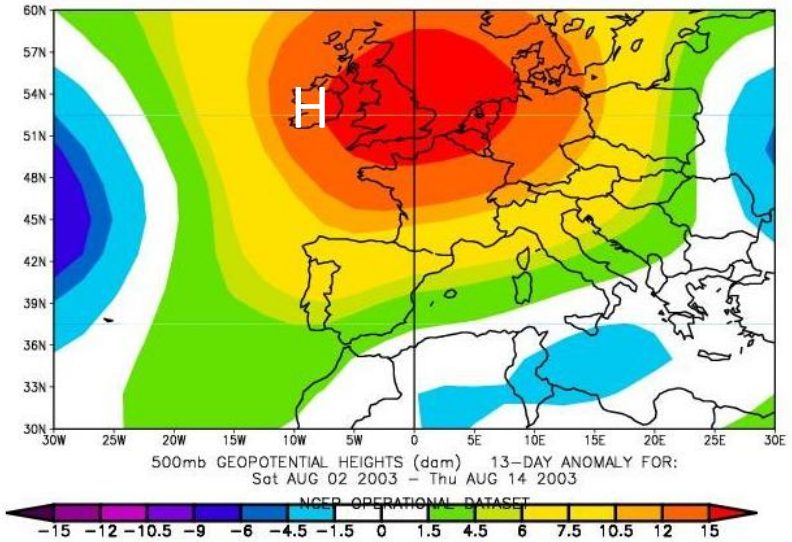
Year-to-year temperatures have been observed to be strongly correlated with ozone

Strong relationship between weather and pollution implies that changes in climate will influence air quality

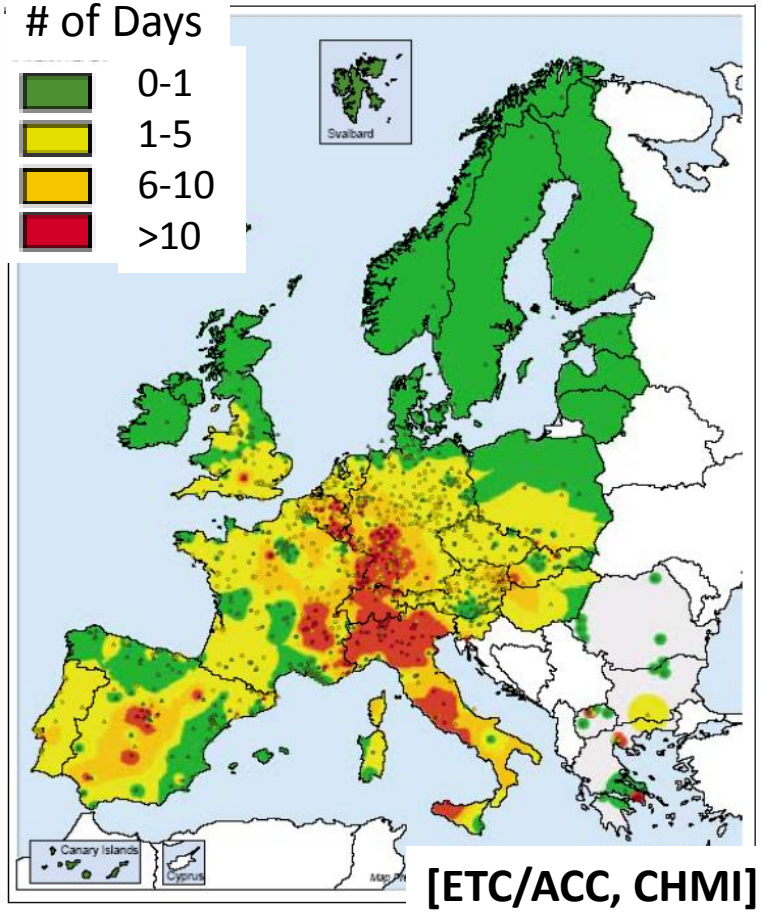
Severe O_3 pollution events associated with air stagnation

Stagnant high pressure system over Europe

(500 hPa geopotential anomaly relative to 1979-1995 for 2-14 August, NCEP)



8-hr O_3 exceedances of 90 ppbv, summer 2003

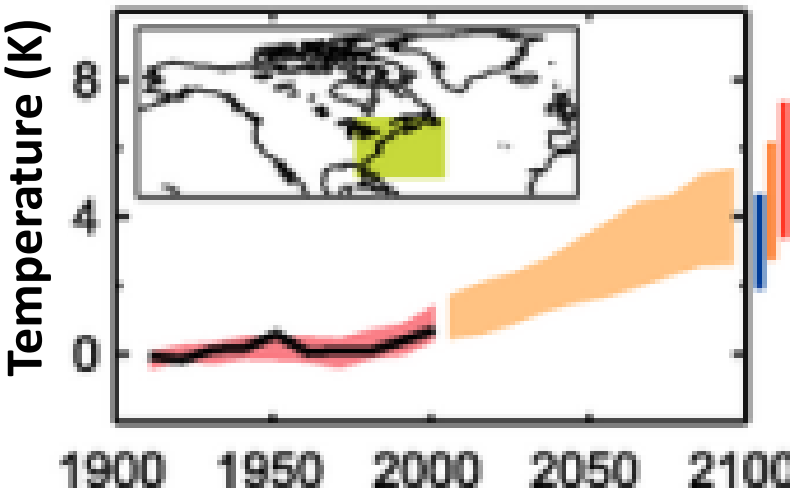


[ETC/ACC, CHMI]

Correlation between surface O_3 and temperature is strongly associated with air stagnation

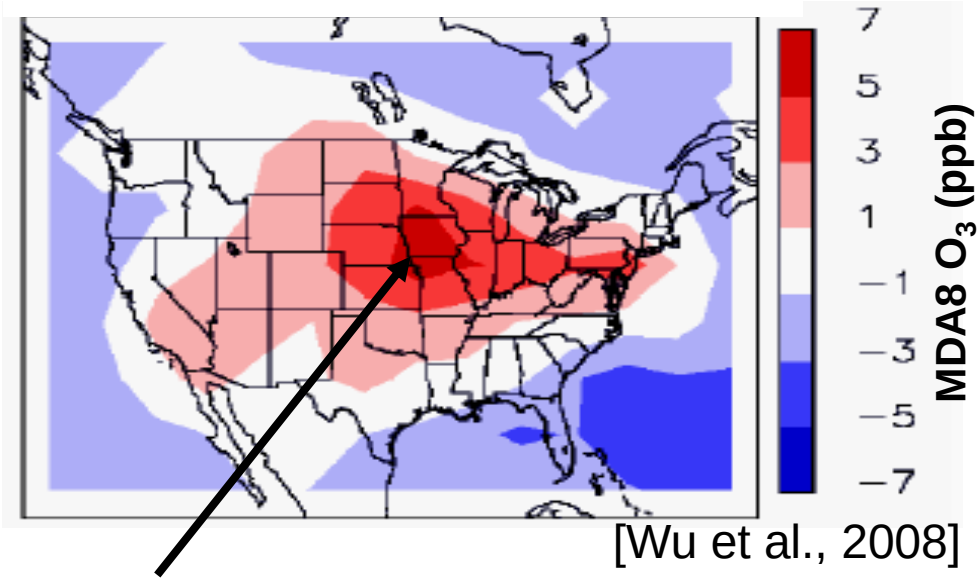
What does a warming planet imply for surface O_3 in the eastern US?

eastern US



[IPCC, AR4, Ch. 11]

Changes in summer 8-h avg. daily maximum ozone from 2000-2050 climate change



[Wu et al., 2008]

Higher temperatures, stagnation

- Models agree that 2000-2050 climate change will increase surface ozone most over polluted regions (3-5 ppb).

- Most models find climate change will exacerbate pollution episodes (up to 10 ppb) due to increased stagnation and higher temperatures.

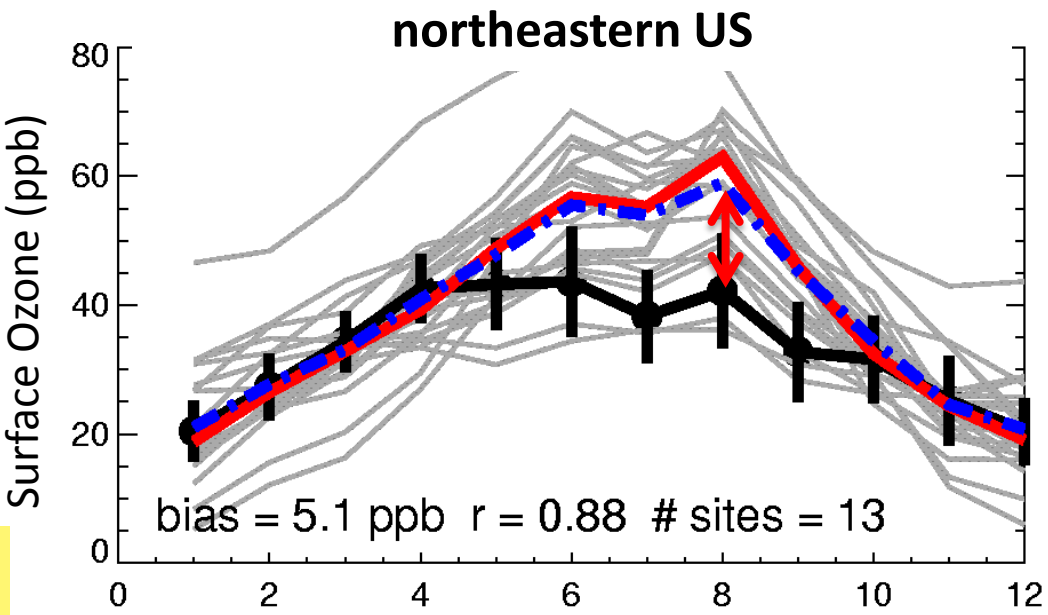
- Models fairly robust in simulating O_3 increases in Northeast and Midwest U.S.

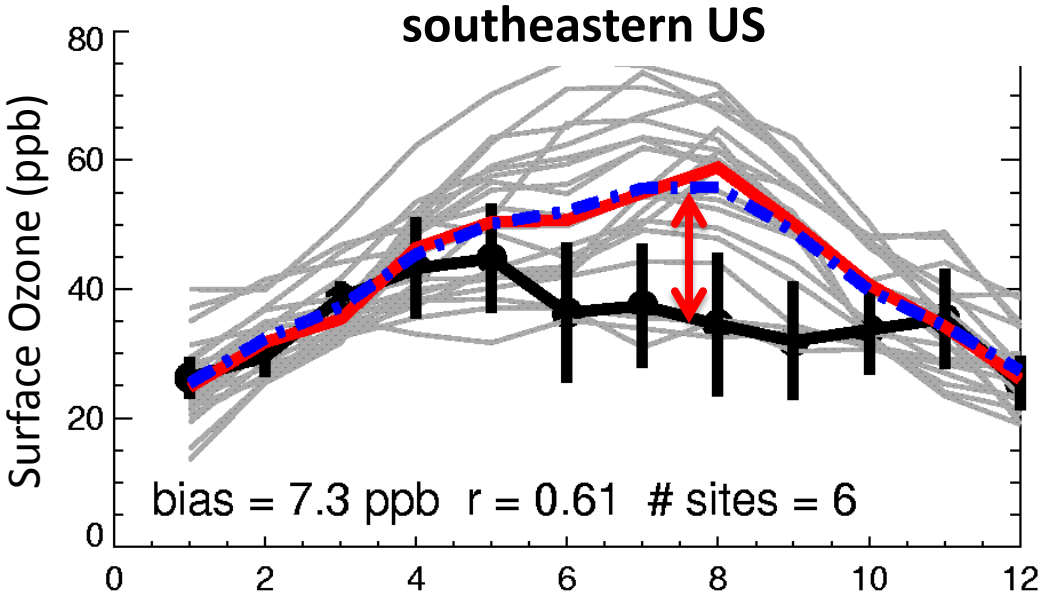
Current generation global models

How accurate are these models at reproducing observed seasonal O_3 concentrations?

Obs. = black
Ensemble mean/median = red/blue

- **A pervasive high summertime O_3 bias exists across both eastern US regions** *[A.M. Fiore, L.W. Horowitz et al., 2009; Murazaki and Hess, 2006; Reidmiller et al., 2009]*
- ***These biases raise concern of the ability of chemistry-climate models to project accurately the response of air pollution to climate change***





Motivating Questions

1) Can we characterize long-term O_3 response to year-to-year temperatures for regions over the eastern US for purposes of chemistry-climate model evaluation?

2) Despite a known modeled ozone bias, can the GFDL AM3 chemistry-climate model represent the ***response*** of surface O_3 to interannual variations in temperature?

3) Do modeled temperature biases contribute to these modeled ozone biases?

We hypothesize that:

Adequate representation of observed, climatological O_3-temperature relationships will help to build confidence in future projections of the air quality response to changes in climate

Representing the O_3 – temperature relationship

We use temperature as a proxy to synthesize the complex effects of meteorological and chemical factors influencing O_3 concentrations

We represent these aggregate effects as a total derivative, $\frac{d[O_3]}{dT}$

The O_3-temperature relationship is thought to represent at least three components in the eastern US:

$$\frac{d[O_3]}{dT} = \underbrace{\frac{\partial[O_3]}{\partial[stagnation]}\frac{\partial[stagnation]}{\partial T}}_{(1)} + \underbrace{\frac{\partial[O_3]}{\partial[PAN]}\frac{\partial[PAN]}{\partial T}}_{(2)} + \underbrace{\frac{\partial[O_3]}{\partial[isoprene]}\frac{\partial[isoprene]}{\partial T}}_{(3)} + \cdots$$

[Jacob et al., 1993; Olszyna et al., 1997]

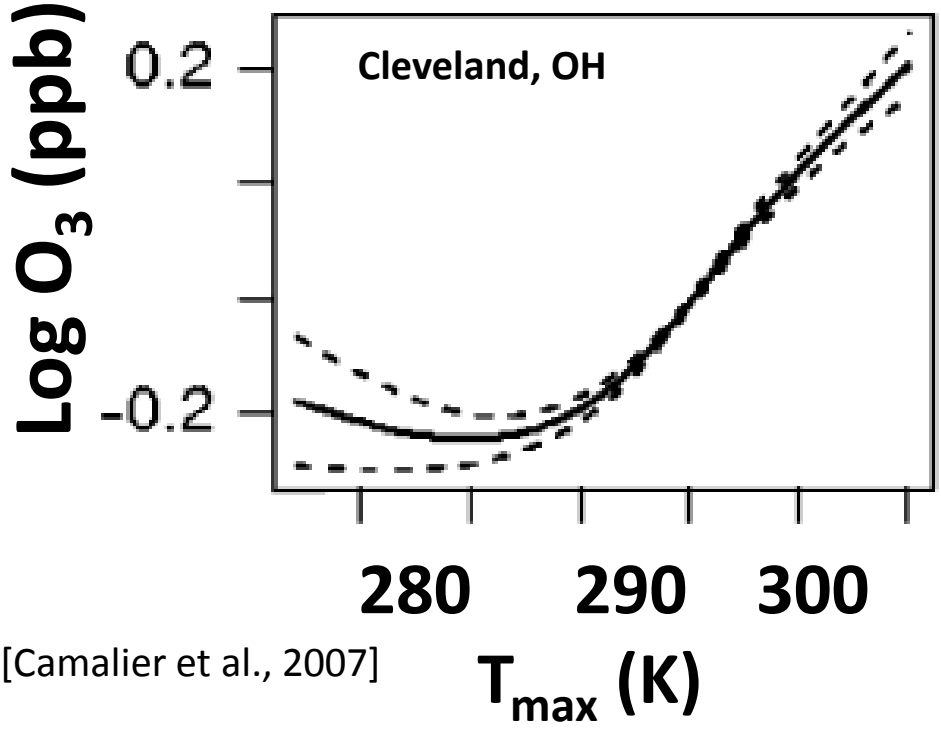
[Sillman and Samson, 1995]

[Meleux et al., 2007; Guenther et al., 2006*]*

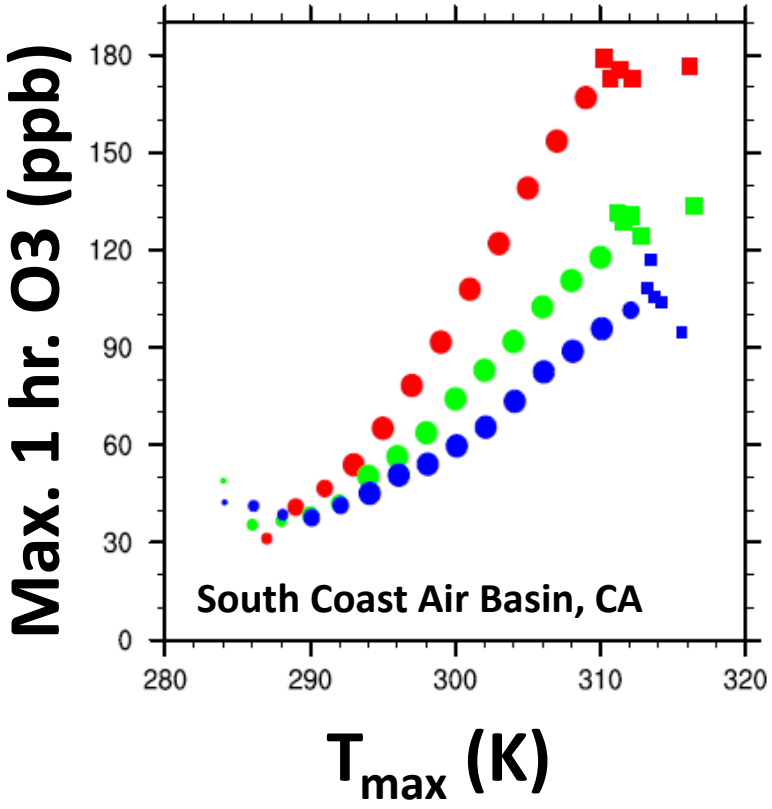
meteorology **chemistry** **emissions**

Over what range of temperatures does O_3 increase?

Ozone's relationship with temperature is non-linear, but it has been observed to be linear for ranges of temperatures…



[Camalier et al., 2007]



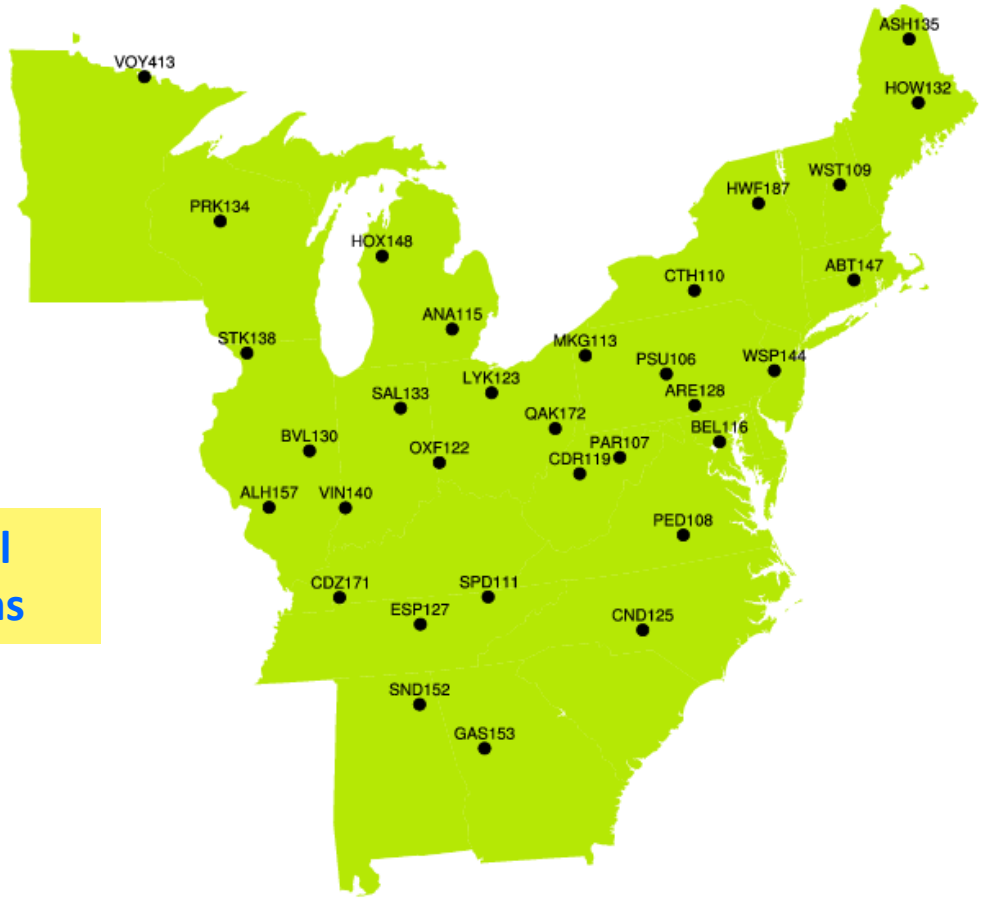
[Steiner et al., 2010]

O_3 found to typically increase linearly between 290-305 K

[Bloomer et al., 2009; Camalier et al., 2007; Sillman and Samson, 1995; Steiner et al., 2010]

Observation network

EPA CASTNet sites used and locations:



co-located meteorological and chemical observations

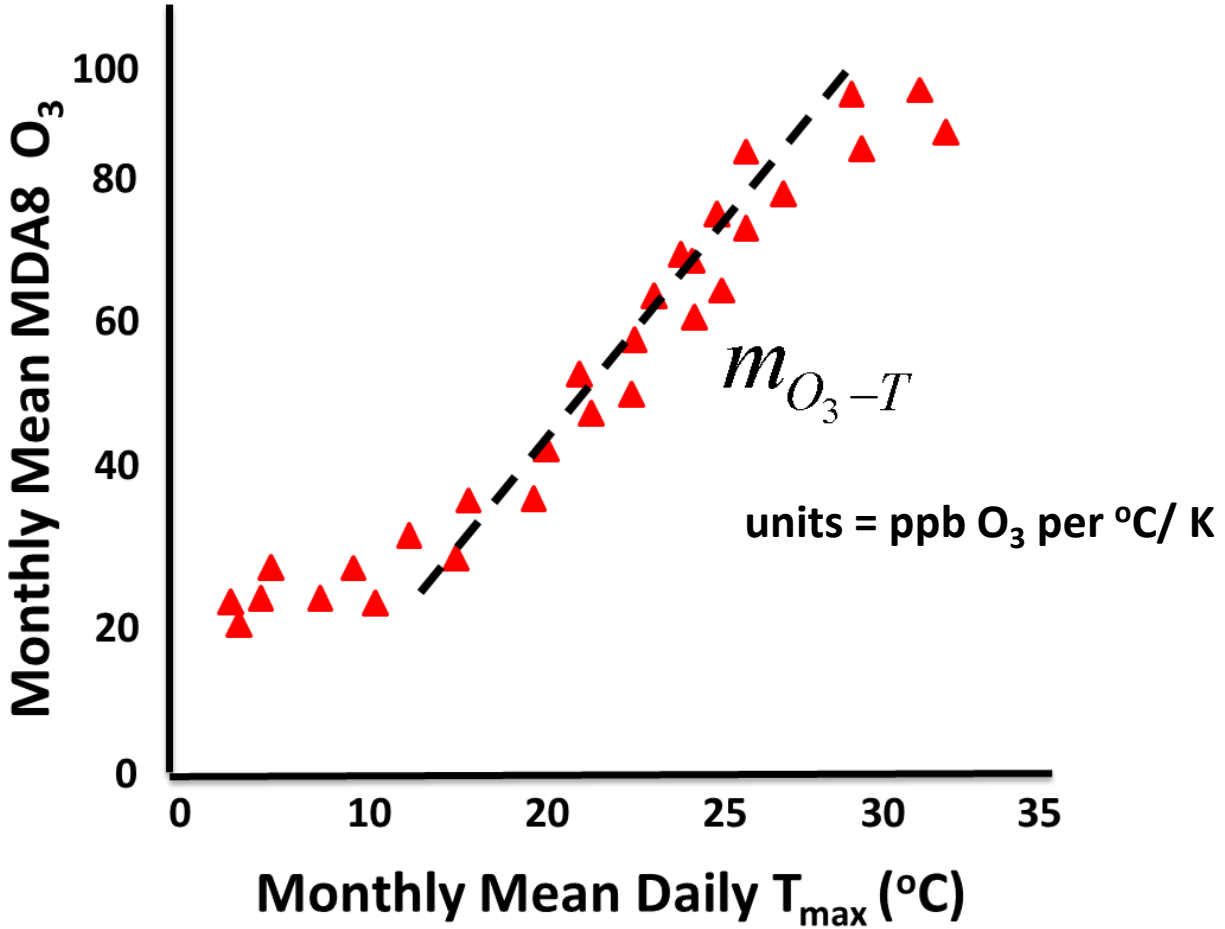
Observations: EPA Clean Air Status and Trends Network (CASTNet; designed for measurements to be representative of the regional scale)

Most sites have record lengths spanning 1988-2009

statistical approach to the O_3-temp relationship

We focus on the warm season over the eastern US where O_3 and temperature are well correlated *[Dawson et al., 2007; Lin et al., 2001; Sillman and Samson, 1995]*

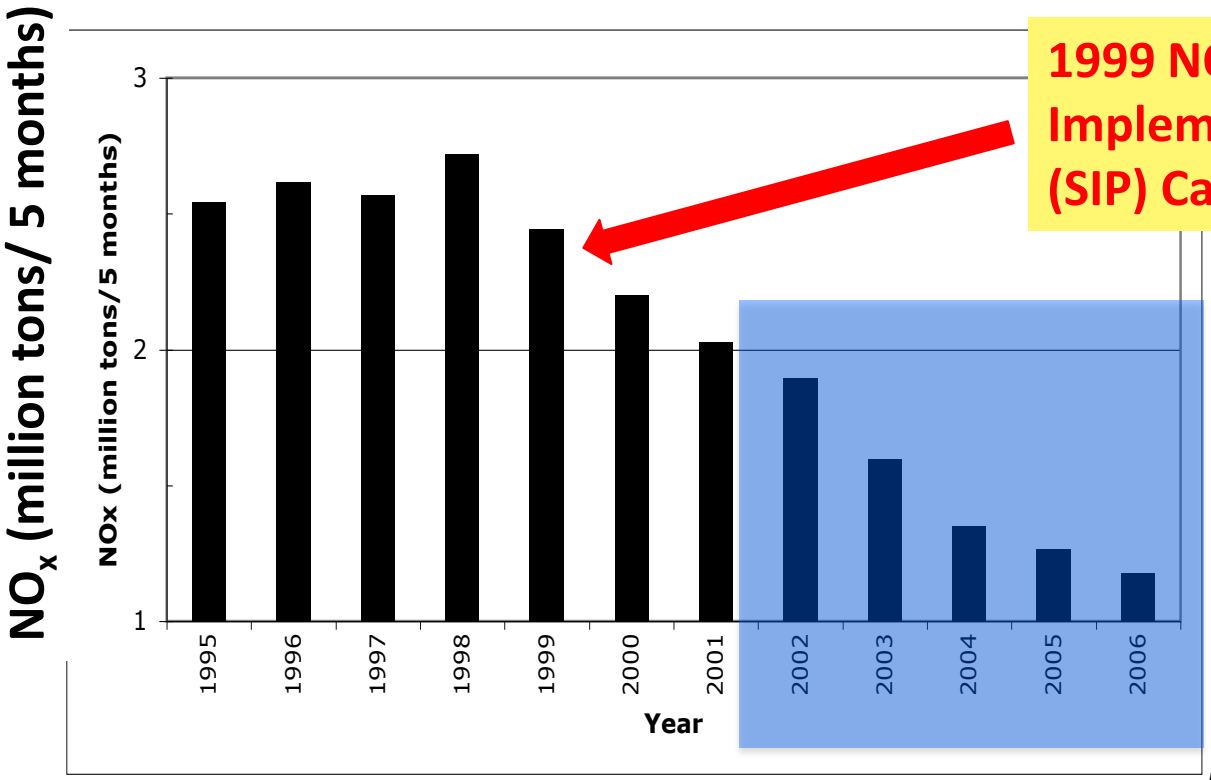
We use maximum daily 8-hour average (MDA8) O_3 and maximum daily surface temperature (T_{max}) to focus on the daytime (deep, well-mixed, boundary layer)



Humans can influence O_3 sensitivity to temperature by changing the O_3 production chemistry

CO
VOC
} NO_x + Sunlight = O_3

National Ozone Season NO_x Emissions from Power Plants



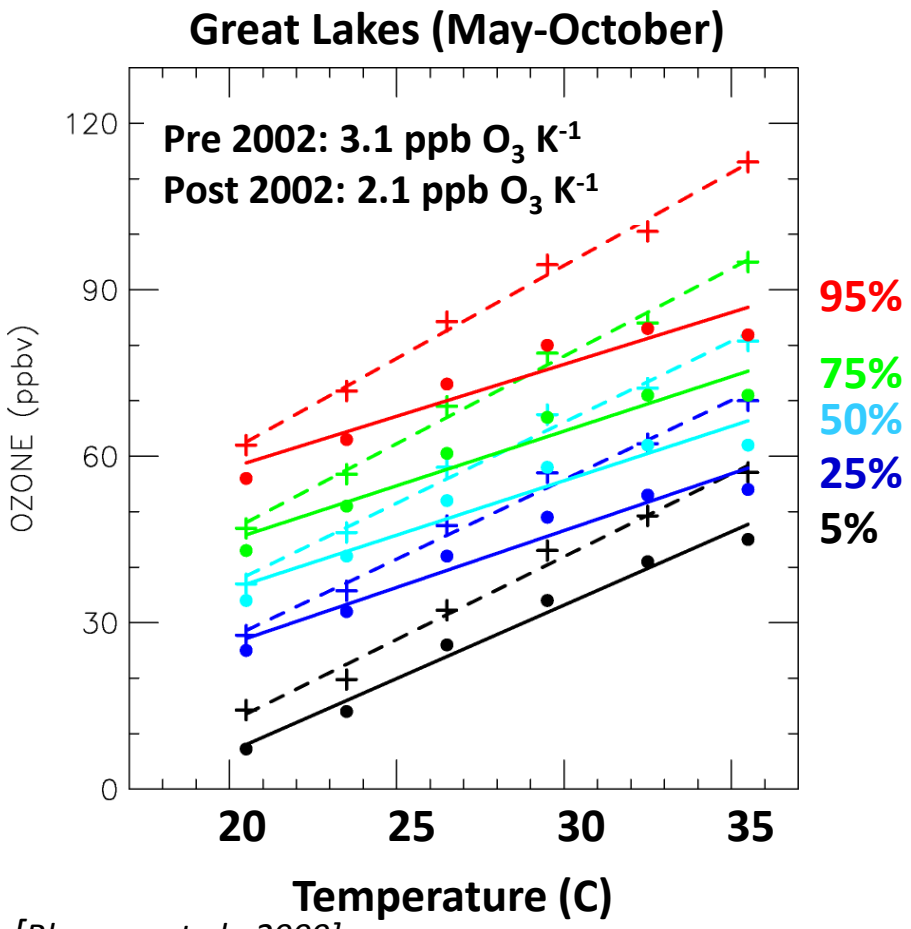
1999 NO_x State Implementation Plan (SIP) Call

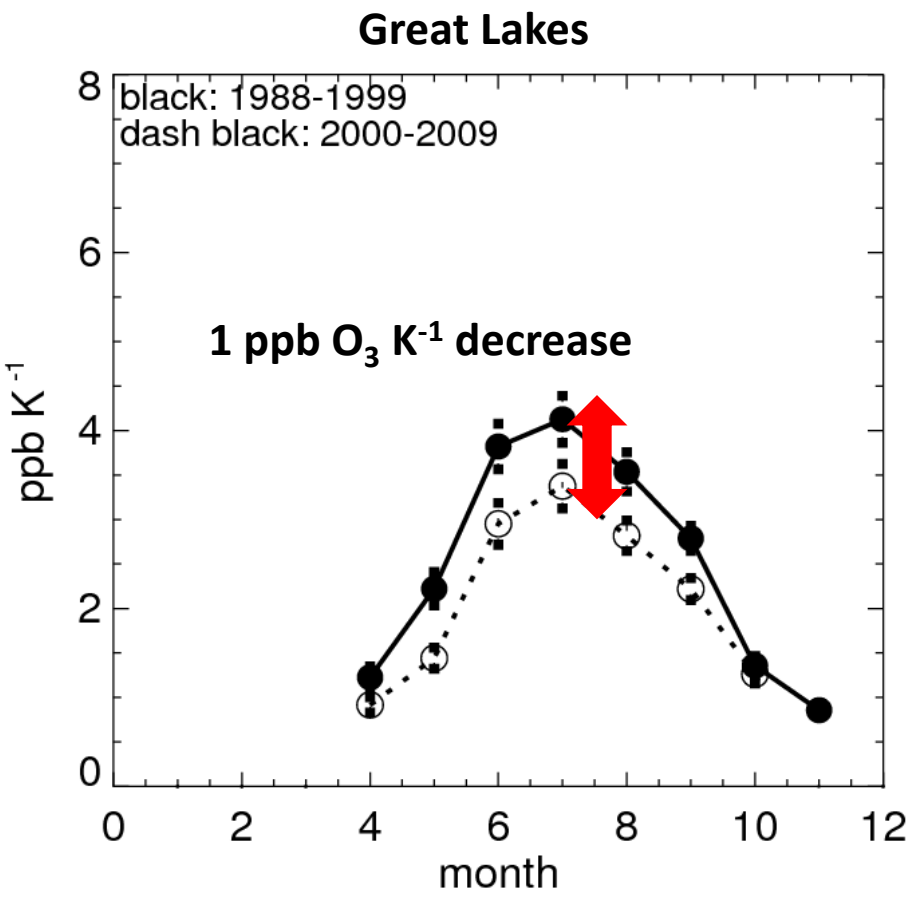
43% decrease in eastern US NO_x emissions!

[c/o US EPA]

Changes to anthropogenic NO_x emissions have a substantial effect on the sensitivity of O_3 to temperature

effects of NO_x emission controls on O_3 sensitivity





[Bloomer et al., 2009]

- **Δ NO*x* emissions decreased ozone levels over the entire distribution**
- **The ozone sensitivities to temperature also decreased across the distribution**
- **Different statistical methods reveal the same 1 ppb O_3 K^{-1} decrease during O_3 season**

AM3 simulations

- **We use a 20-year (1981—2000) run of the GFDL AM3 CCM** ***[Donner et al., 2011; Naik et al., in prep]***
    - **Interactive isoprene (responds to solar radiation and temperature) (MEGAN) following that used in MOZART-4** ***[Emmons et al., 2010]***
- **Forcings:**
    - **Observed SSTs and sea ice** ***[Rayner et al., 2003]***
    - **ACCMIP aerosol and O3 precursor emissions (as used in CM3 CMIP5 simulations)** ***[Lamarque et al., 2010]***

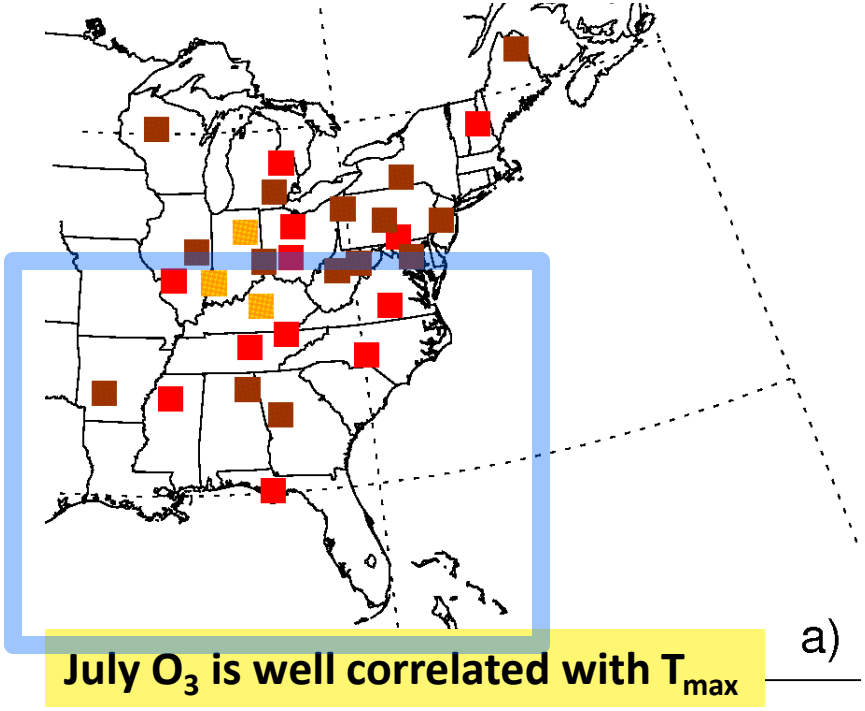
Little to no change in eastern US NO_x emissions in model run

	1980	1990	2000
NO_x	4.23 Tg N	4.40 Tg N	4.29 Tg N

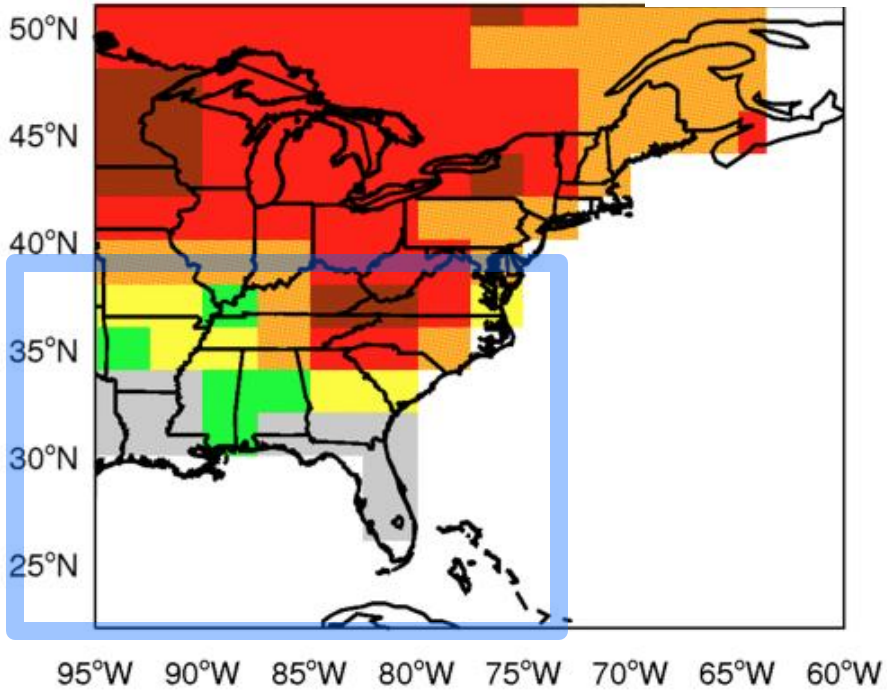
"climatological" O_3-temperature relationships

correlating MDA8 O_3 and daily T_{max}

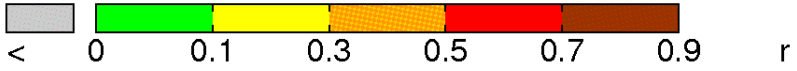
July CASTNet correlation (r) 1988-1999



July GFDL AM3 correlation (r) 1981-2000



July O_3 is well correlated with T_{max}

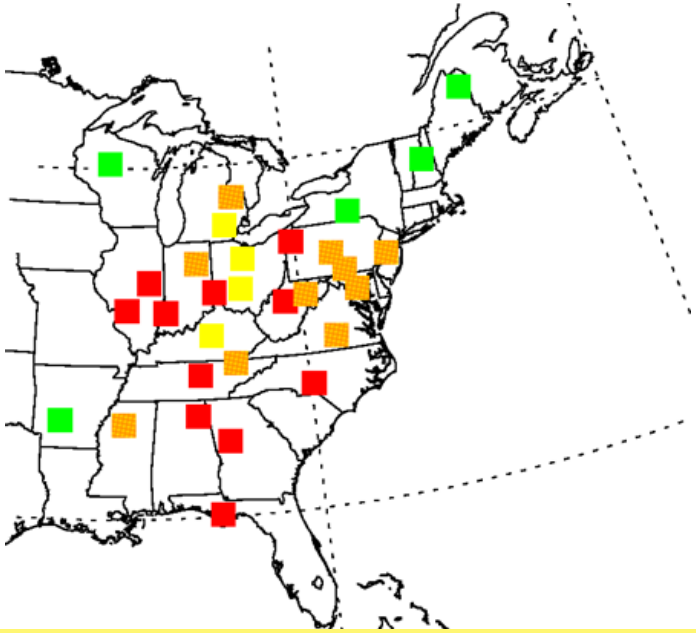


correlations too low in southern US

-problem representing inflow of marine air, convective ventilation, isoprene chemistry in this region?

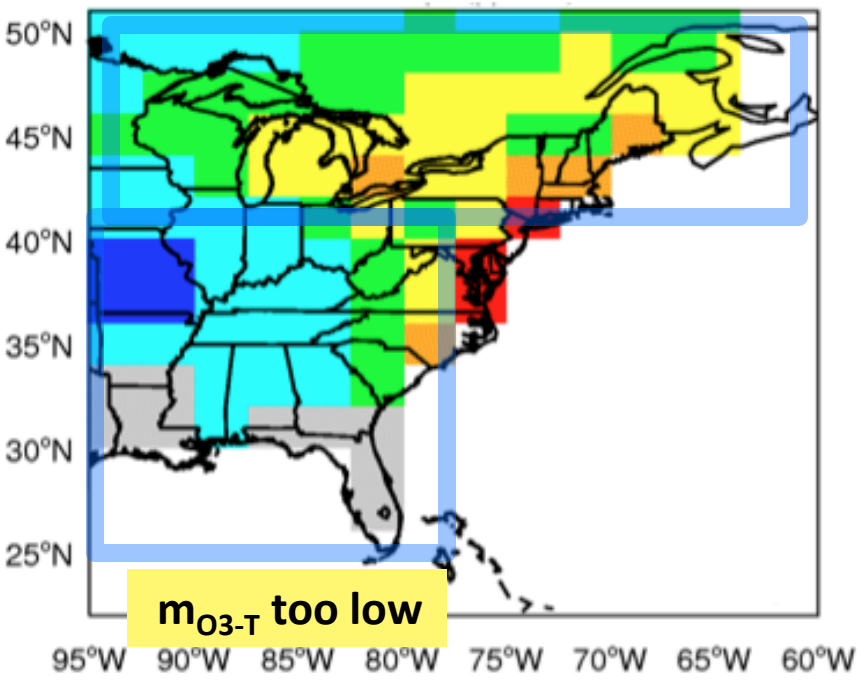
"climatological" O_3-temperature relationships

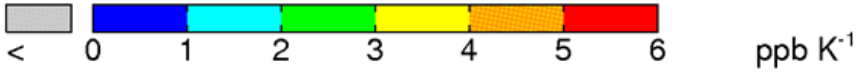
July CASTNet slope (ppb K^{-1}) 1988-1999



July m_{O3-T} highest in Mid-Atlantic and southern US

July CASTNet slope (ppb K^{-1}) 1981-2000

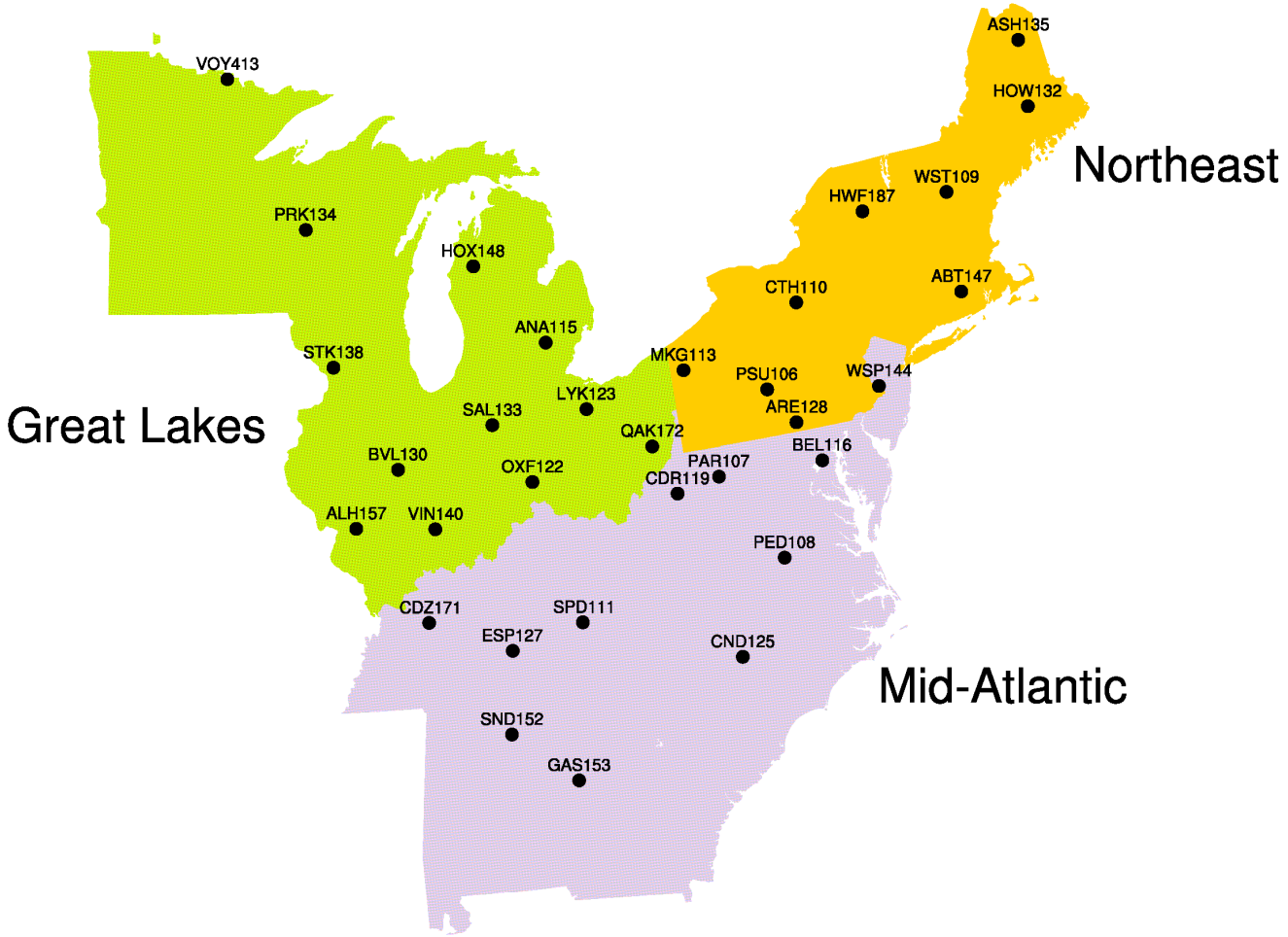




GFDL AM3 produces range of m_{O3-T} over Northeast and portions of the Great Lakes

Remains unclear why GFDL AM3 struggles in Mid-Atlantic and southern US

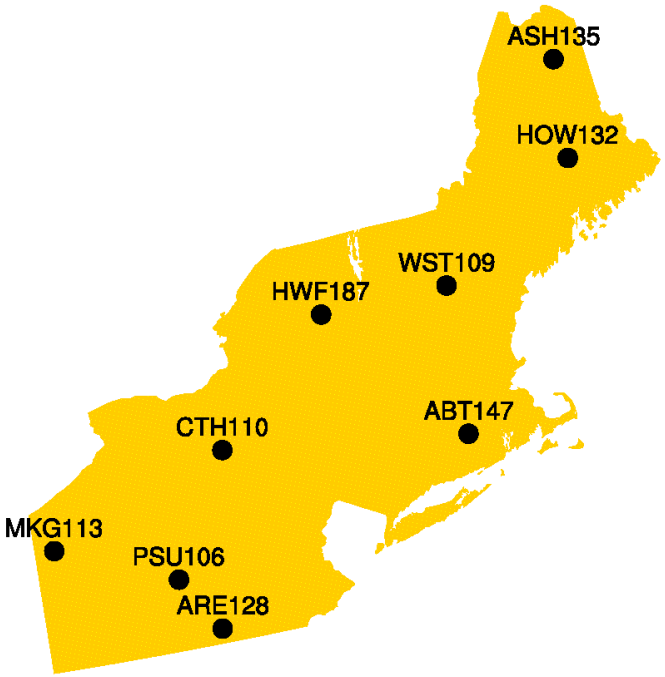
Regional approach to characterizing O_3-temperature relationships



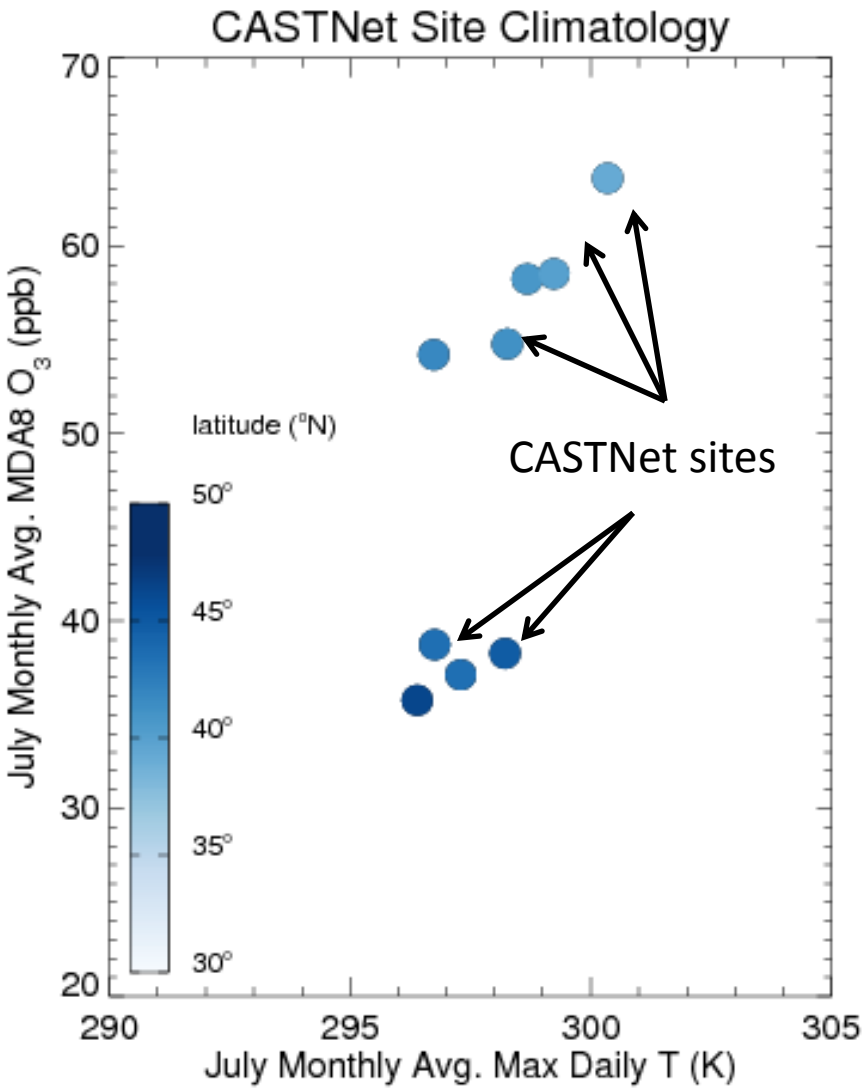
We group CASTNet sites into chemically and meteorologically coherent regions

Motivated by past statistical analyses ***[Bloomer et al., 2009; Eder et al., 1993; Lehman et al., 2004]***

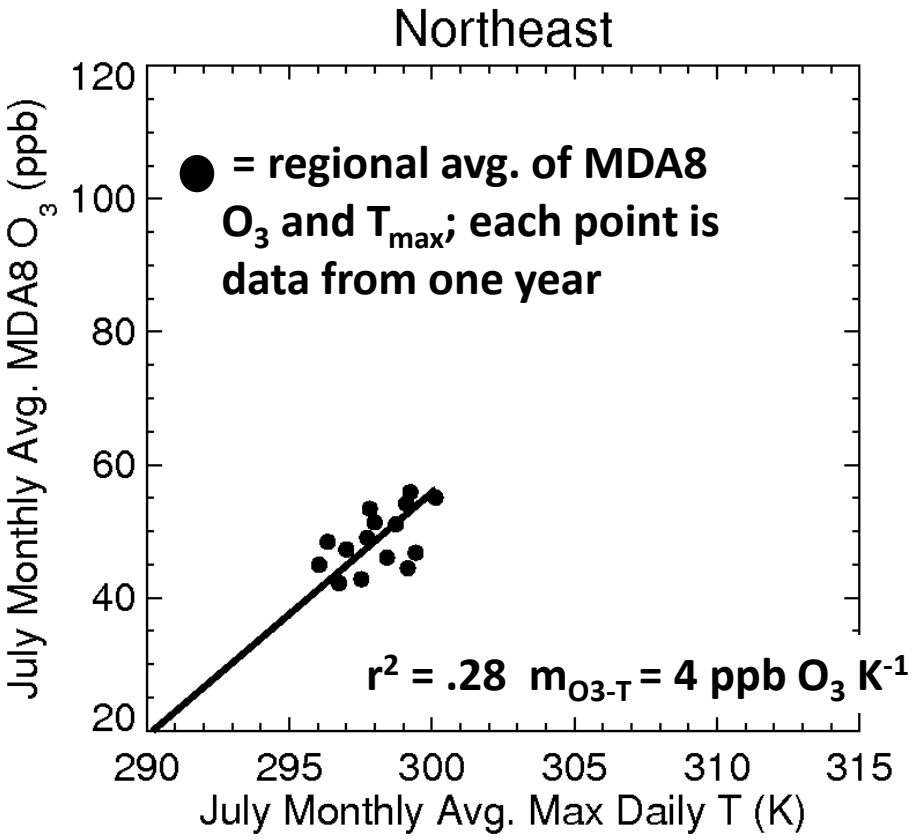
Regional approach: Northeast



We average over all CASTNet sites to isolate the regional response of O_3 to temperature

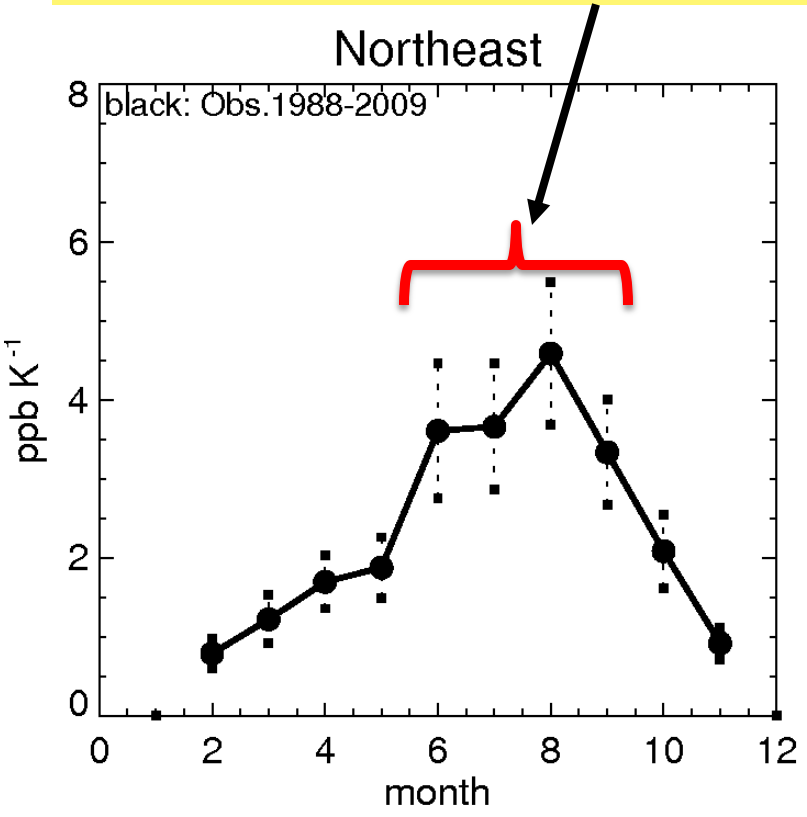


Regional approach: Northeast

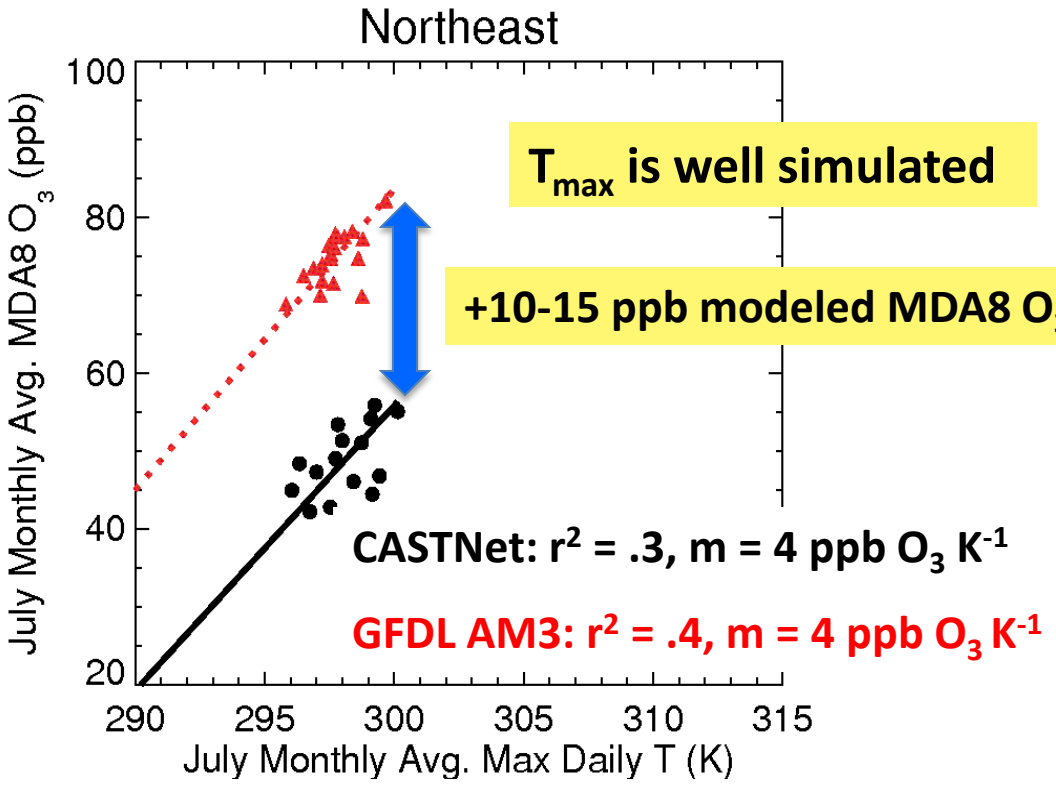


Large standard errors highlight the need for longer datasets

highest O_3 sensitivities to temperature in summer (4-5 ppb O_3 K^{-1})



Regional approach: Northeast



T_{max} is well simulated

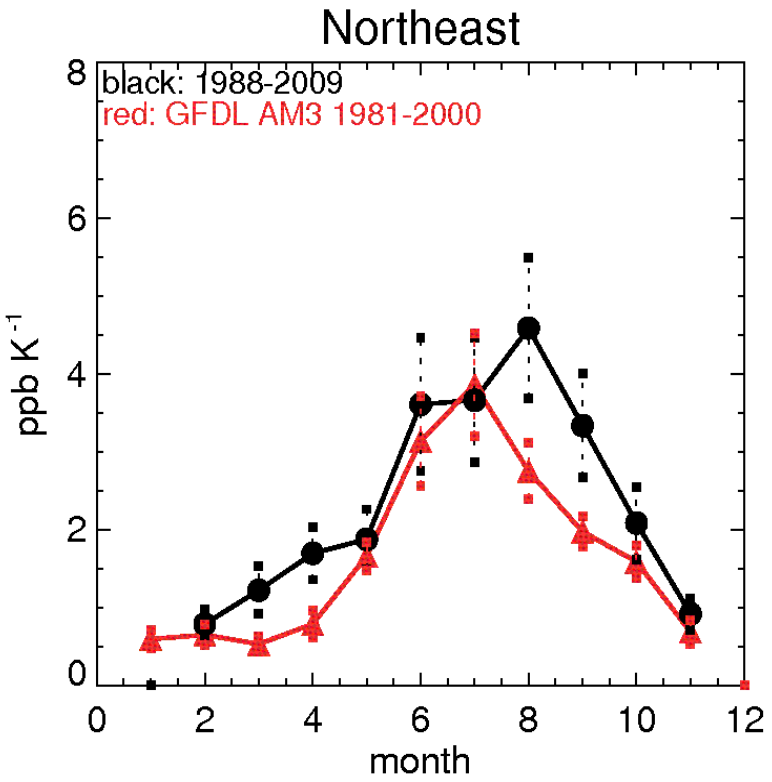
+10-15 ppb modeled MDA8 O_3 bias

CASTNet: r^2 = .3, m = 4 ppb O_3 K^{-1}

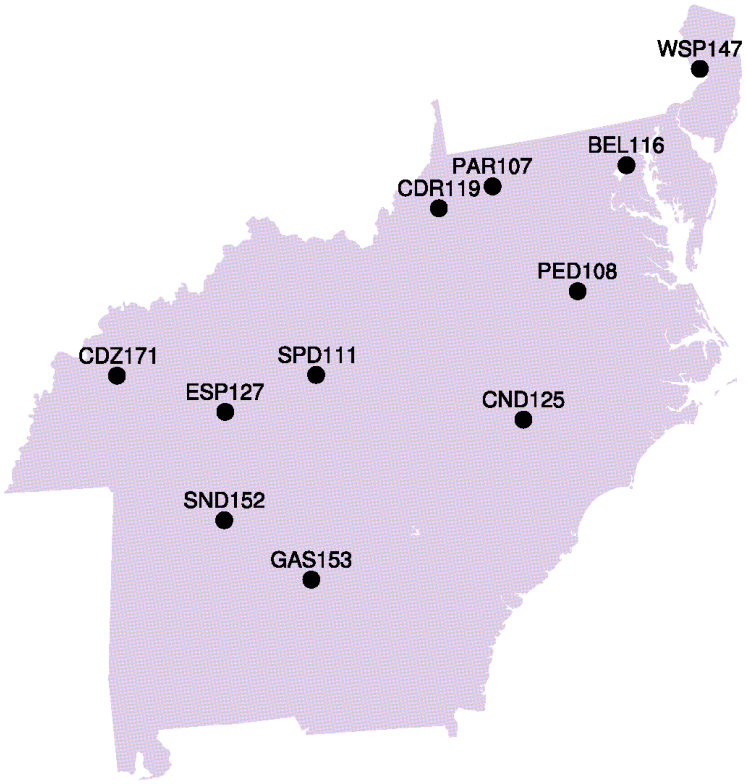
GFDL AM3: r^2 = .4, m = 4 ppb O_3 K^{-1}

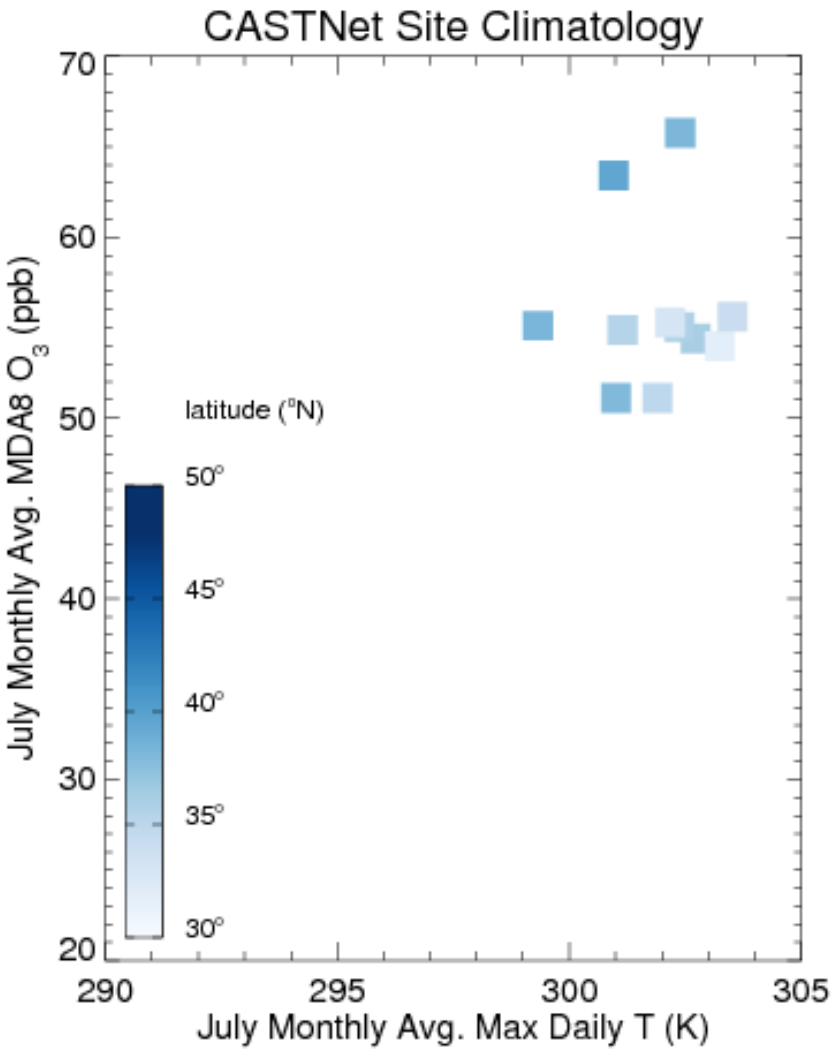
Despite the presence of excess modeled MDA8 O_3…

MDA8 O_3 sensitivity to year-to-year variations in T_{max} are reproduced by GFDL AM3 in the Northeast



Regional approach: Mid-Atlantic

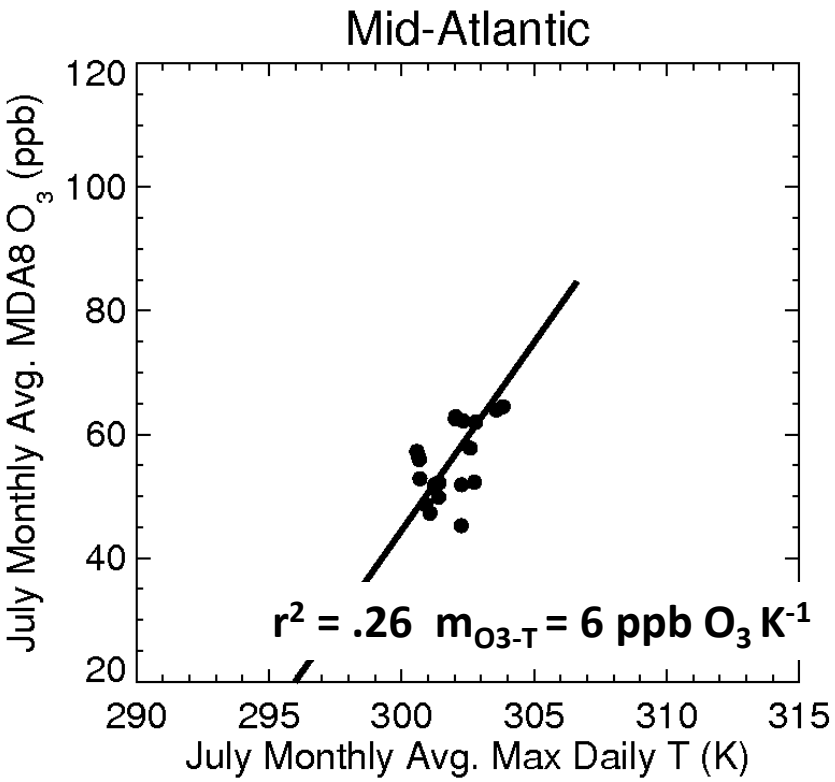


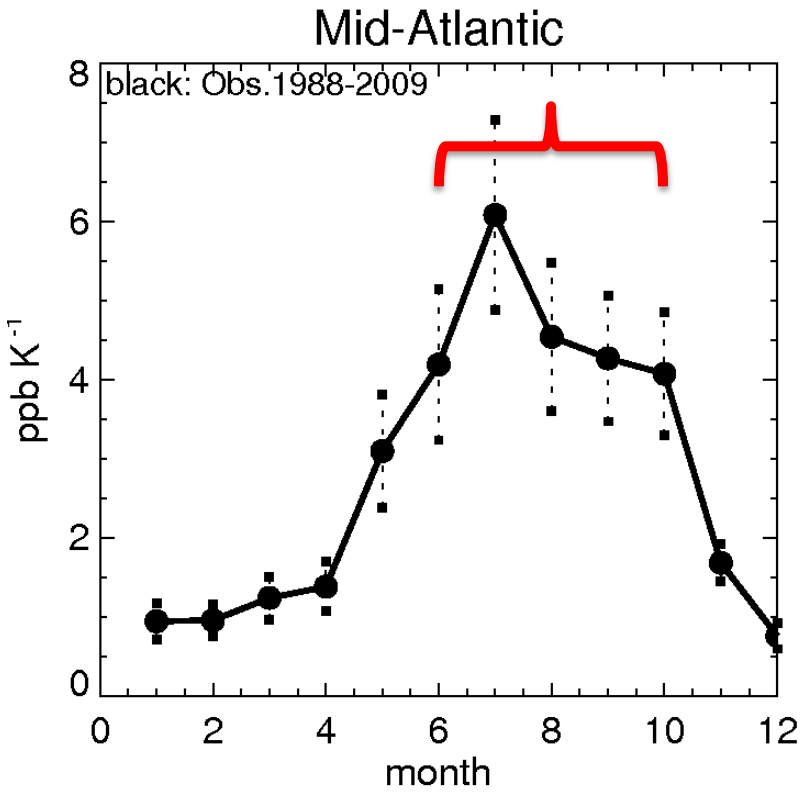


Again, we average over all CASTNet sites to isolate the regional response of O_3 to temperature

Regional approach: Mid-Atlantic

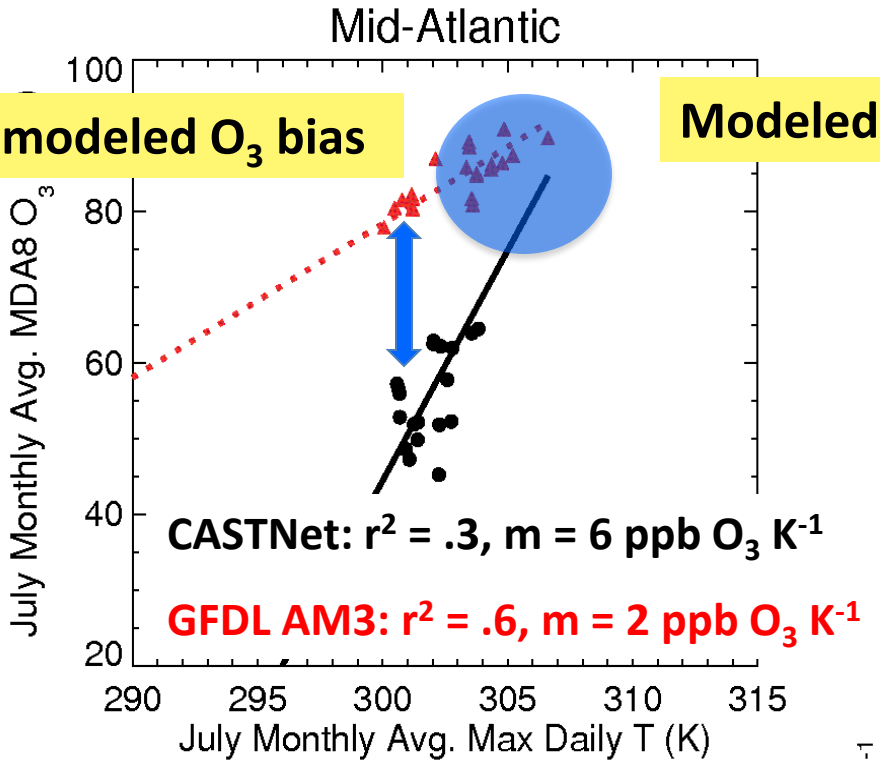
Highest O_3 sensitivities to temperature are in summer (4-6 ppb O_3 K^{-1})



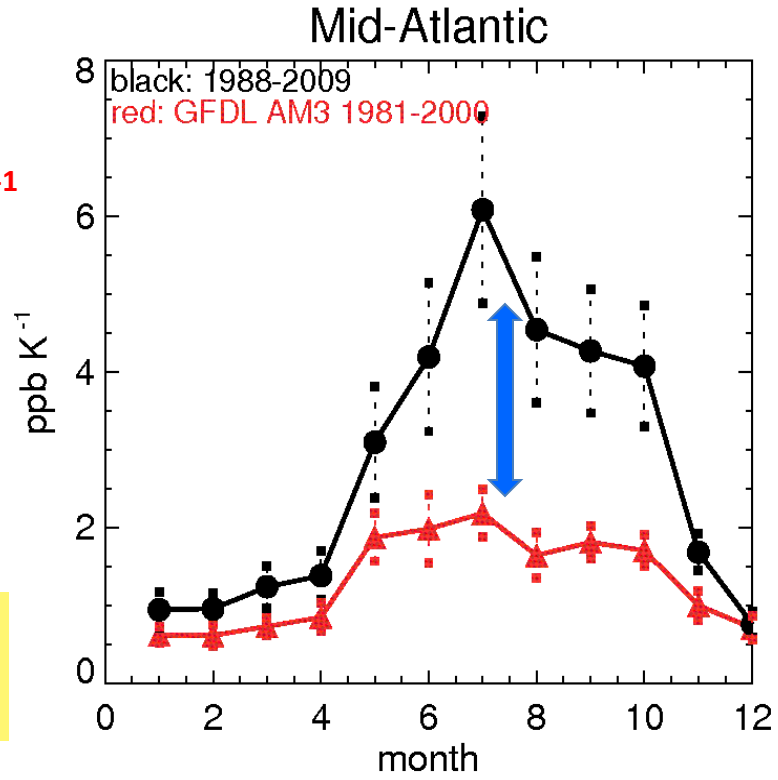


Regional approach: Mid-Atlantic

10-30 ppb modeled O_3 bias



Modeled T_{max} are too large

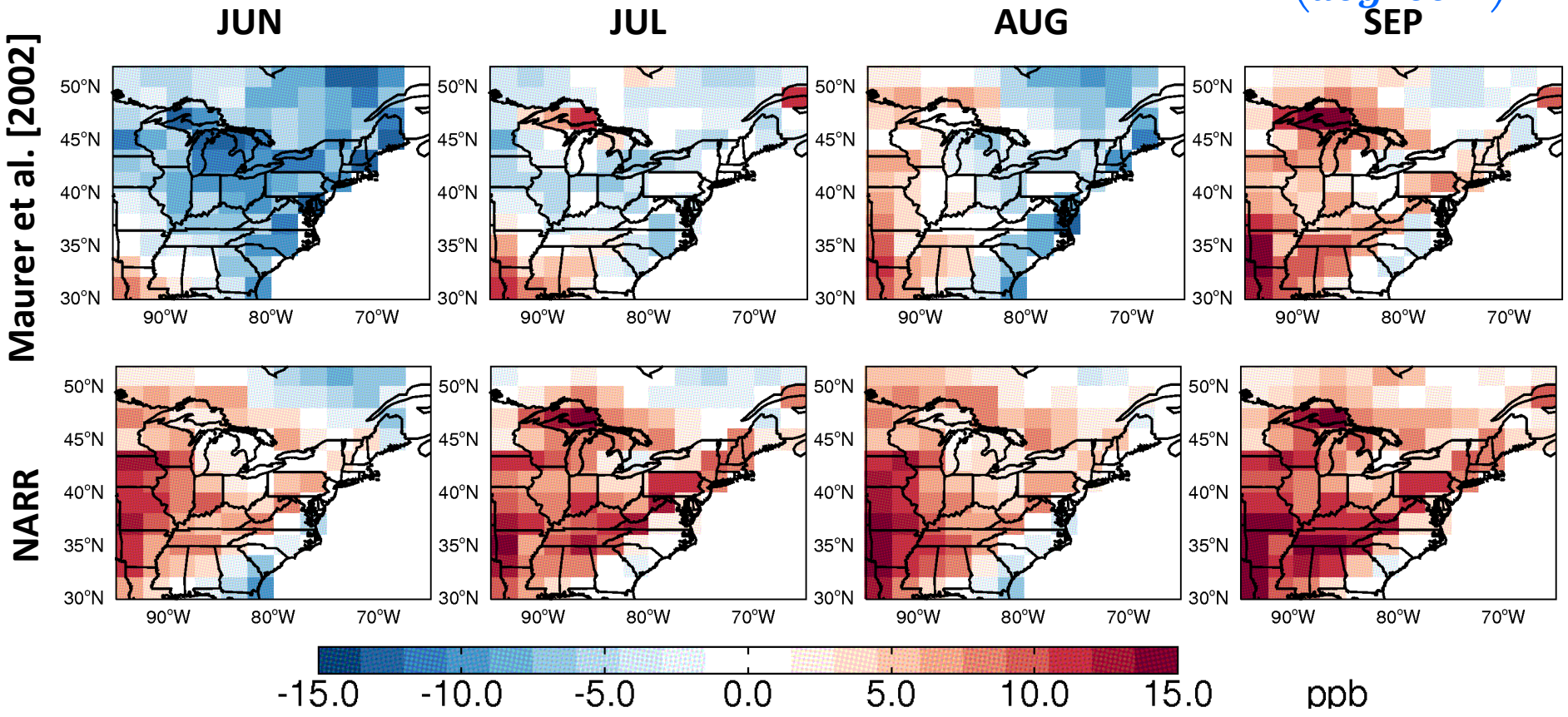


model slopes are ~4 ppb O_3 K^{-1} too low in the summer months

What effect does T_{max} bias have on O_3 over the eastern US?

Modeled t_{max} bias and O_3 sensitivity

multiply T_{max} biases by mean regional sensitivity of 3 ppb O_3 K^{-1} $\Delta T_{max} * 3 \left(\frac{ppb\ O_3}{degree\ K} \right)$



T_{max} biases are responsible for **up to 10-15 ppb** of the summer O_3 bias, specifically in the interior of the Mid-Atlantic region

➢ **cannot be the major driver of the large-scale O_3 bias**

Conclusions

Despite modeled O_3 biases, the GFDL AM3 reproduces $m_{O3\text{-}T}$ in the Northeast, although it underestimates $m_{O3\text{-}T}$ by 2–4 ppb K^{-1} in the summer over the Mid-Atlantic

- **model skill at simulating fundamental meteorological processes may be contributing to the inaccuracies in producing $m_{O3\text{-}T}$ over the Mid-Atlantic**

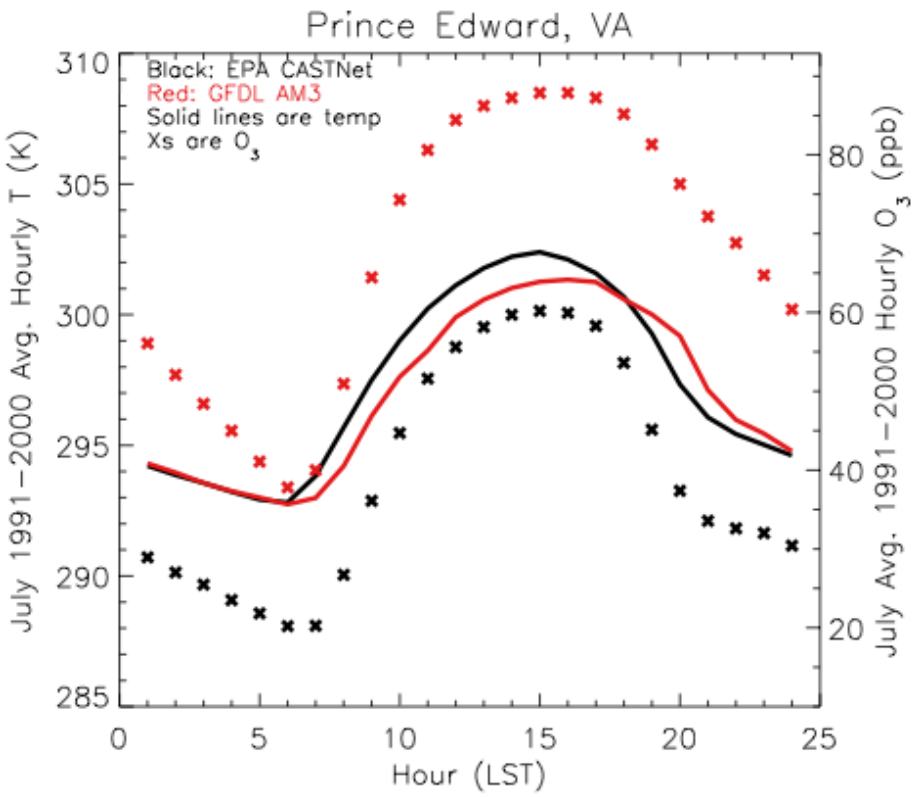
We estimate a maximum contribution of 10–15 ppb MDA8 O_3 from simulated T_{max} biases over the Mid-Atlantic

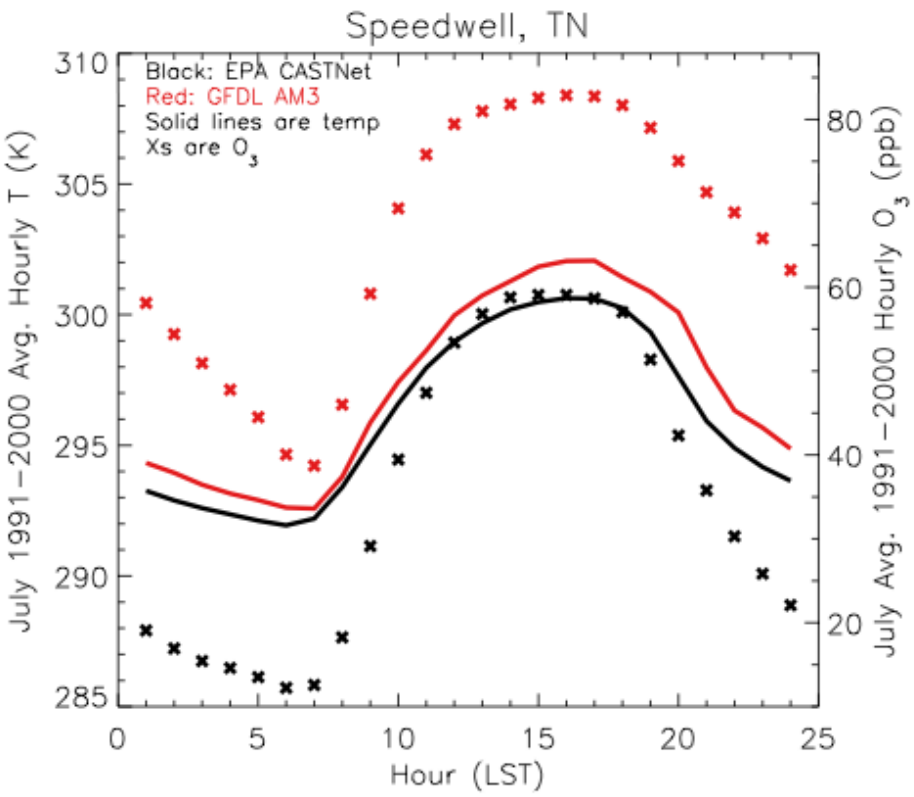
- **We find modeled (+) T_{max} biases are not the major driver of the large-scale excess modeled O_3**

supplemental slides

evaluating modeled diurnal temperature and O_3

When diurnal temperature biases are highest, are the O_3 biases correspondingly highest?





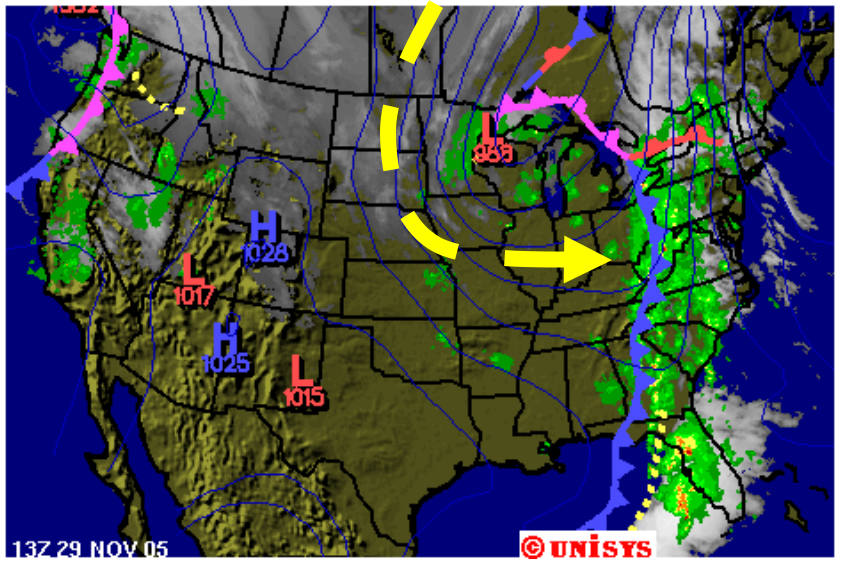
Why does the model struggle in the southeastern US?

Fundamentally different meteorological processes modulate O_3 levels in the southern and northern halves of the eastern US:

- In the Northeast: pollutant ventilation is known to be driven by migratory cyclones associated with cold fronts [Leibensperger et al., 2008; Logan, 1989, Vukovich, 1995]

- In the Southeast: Deep convection and inflow from the Gulf of Mexico are known to ventilate O_3 in the boundary layer [Li et al., 2005]

cyclonic ventilation of the eastern U.S.

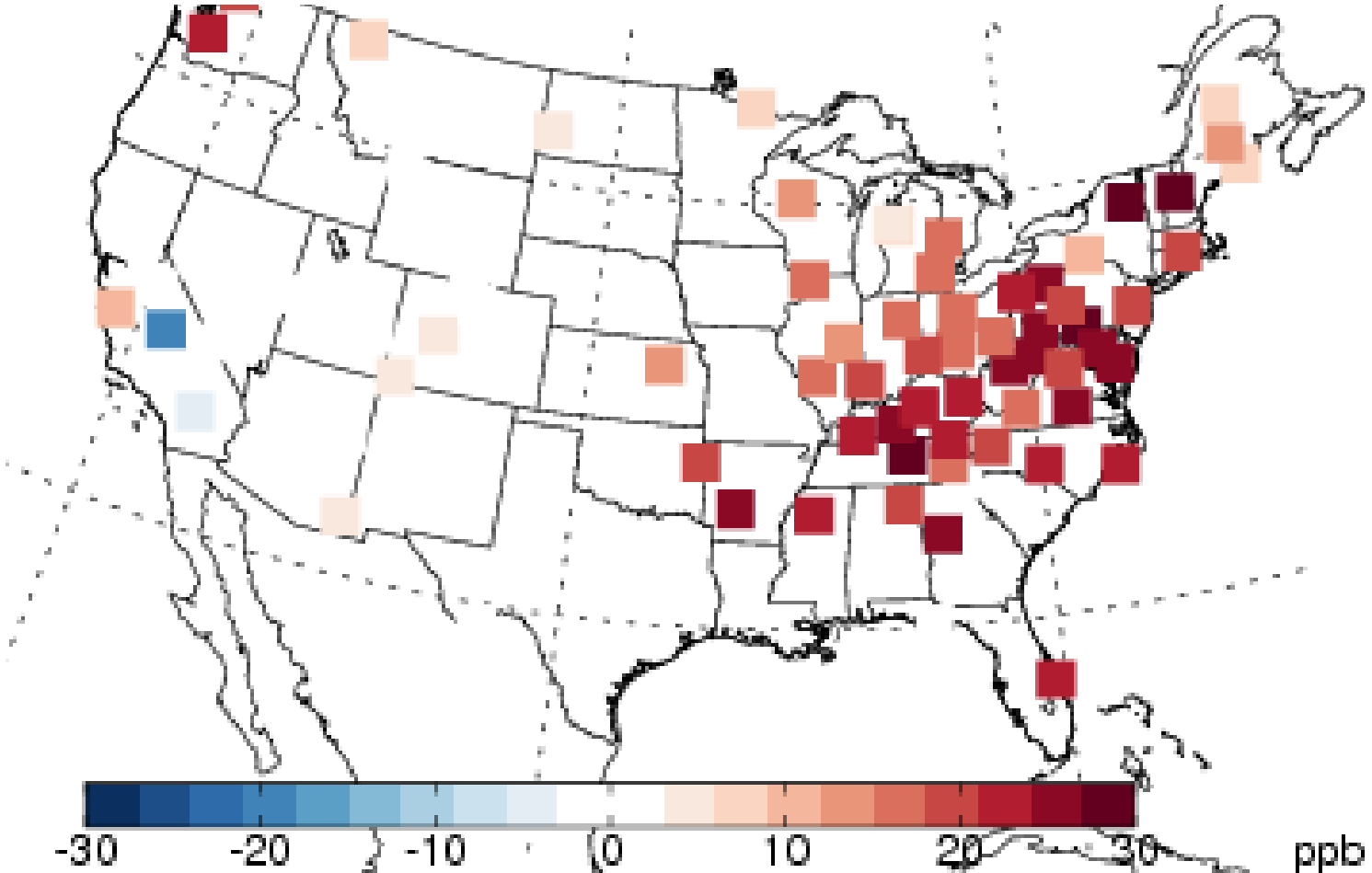


- The skill of the GFDL AM3 chemistry-climate model in simulating these meteorological processes may be help explain why O3-temp sensitivities are not accurately produced

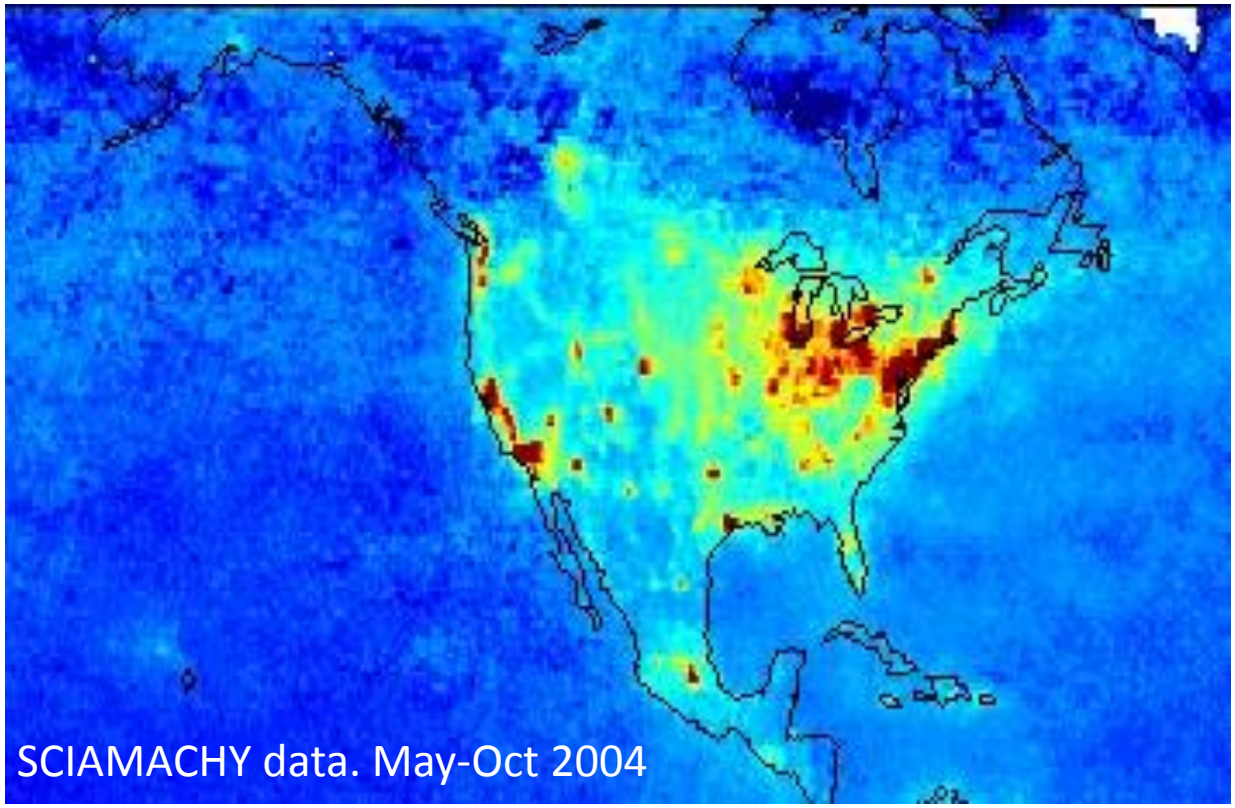
GFDL AM3 CCM eastern U.S. summertime O_3 bias

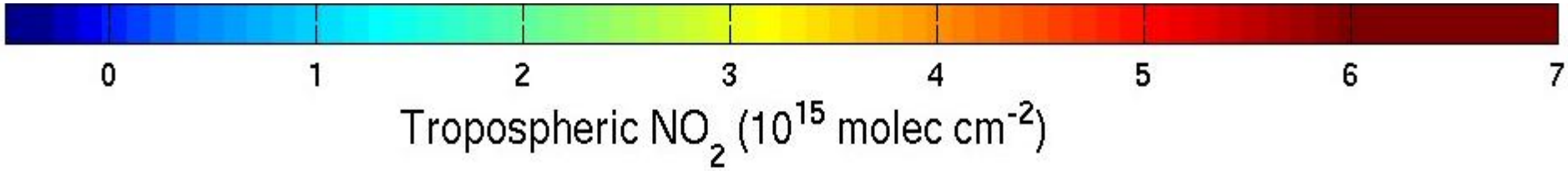
GFDL AM3 CCM has a high O_3 bias in summer months in the eastern U.S. [10-30 ppb]

June monthly mean MDA8 O_3 Bias (GFDL minus CASTNet)



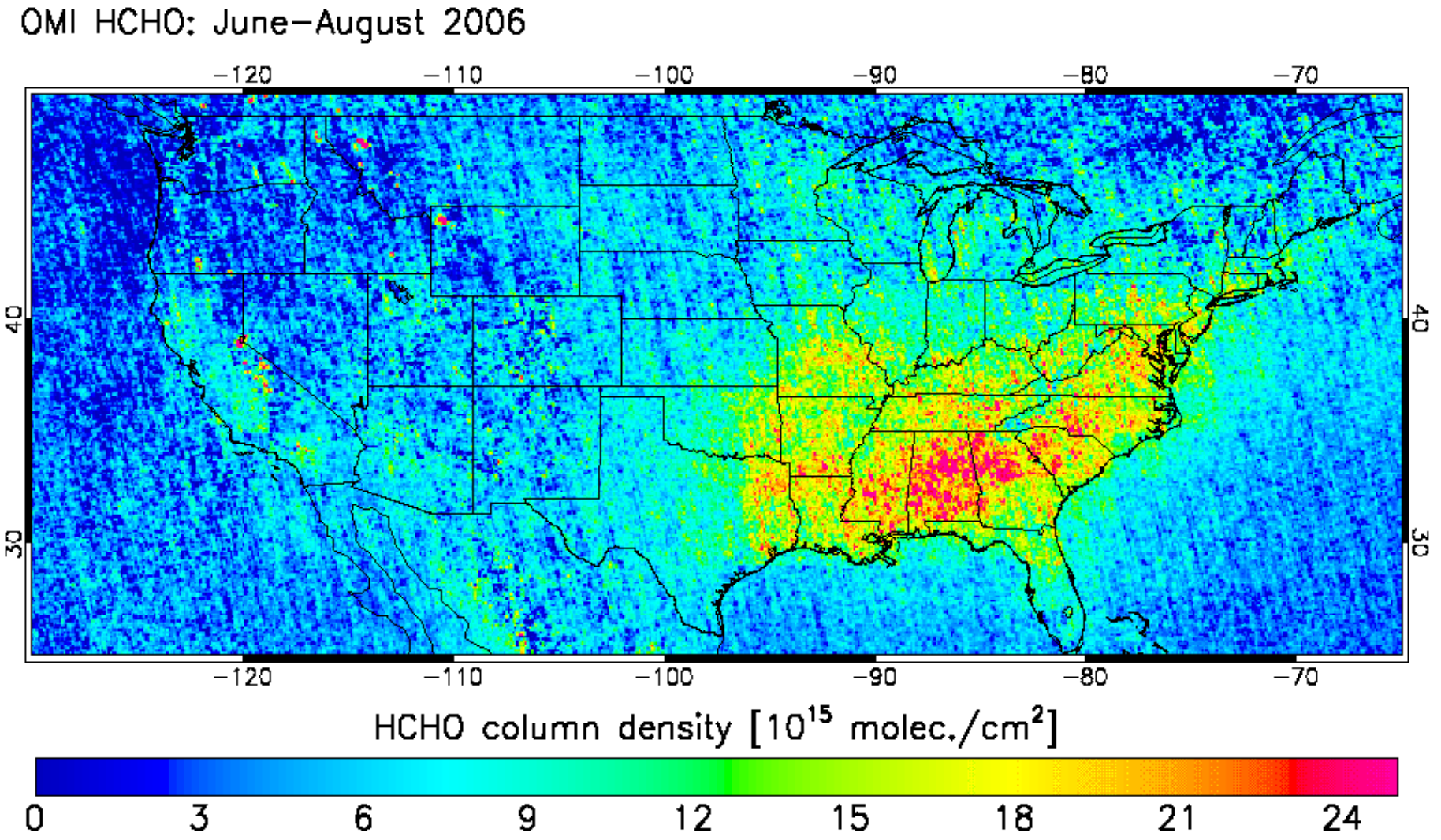
Spatial distribution of NA tropospheric NO_2





[R.V. Martin, Dalhousie U.]

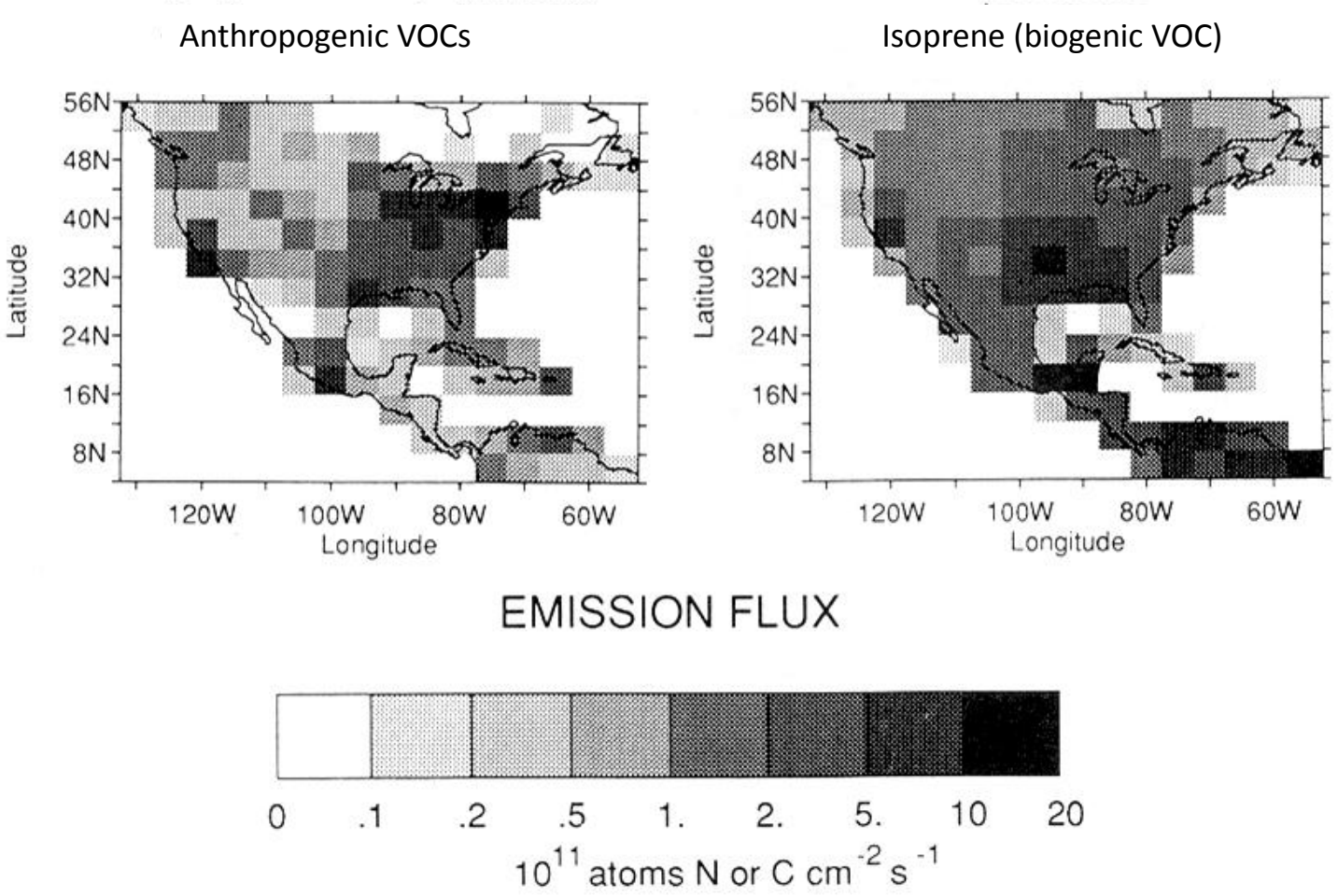
Biogenic VOC (isoprene) column measurements



Millet et al. [2008]

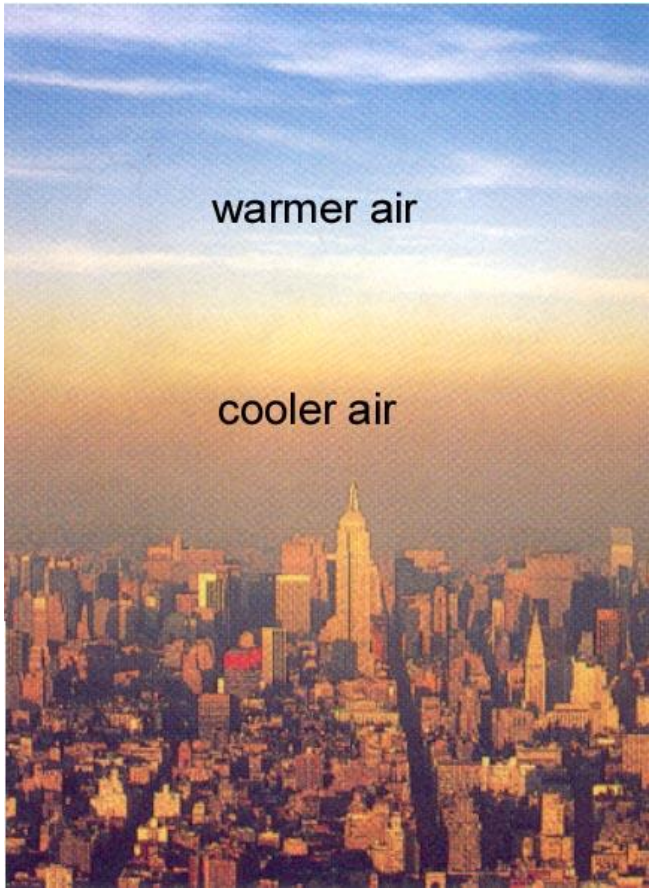
Emissions of VOCs spatially vary

Switches polluted areas in U.S. from NO_x-saturated to NO_x-limited regime!
recognized in Revised Clean Air Act of 1999

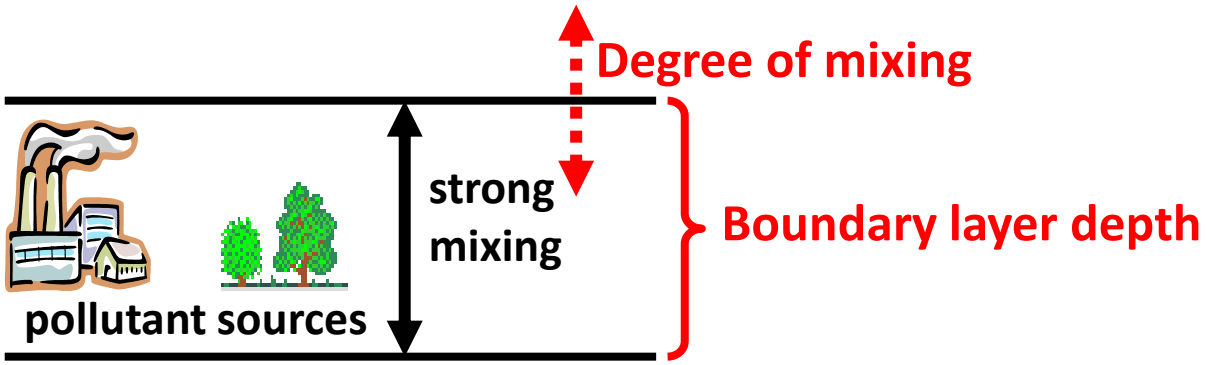


Jacob et al., J. Geophys. Res. [1993]

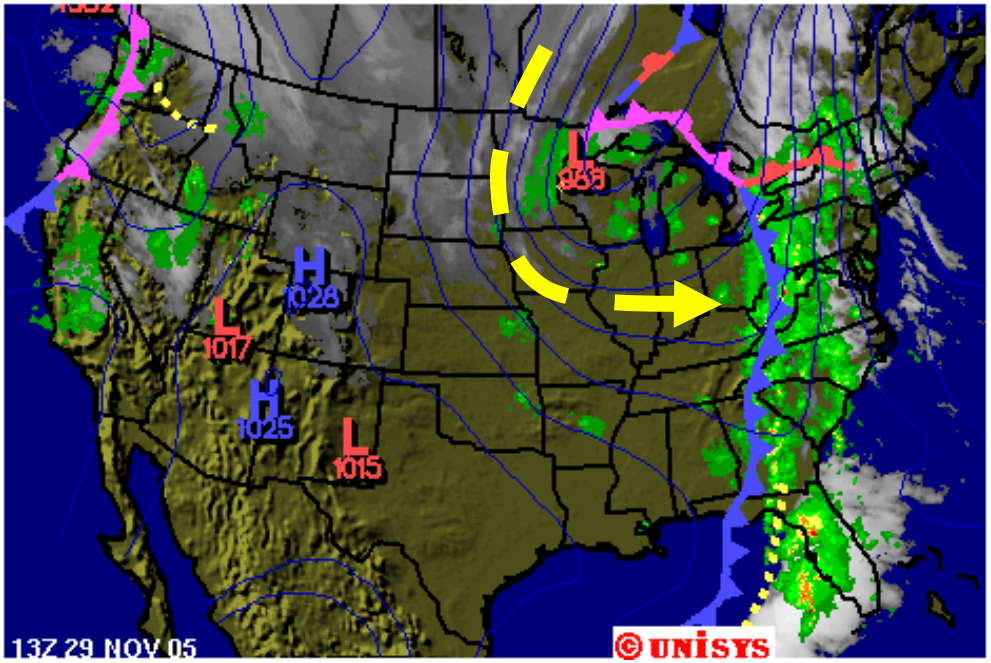
(1) Regional stagnation/ ventilation



[Manhattan, NY]



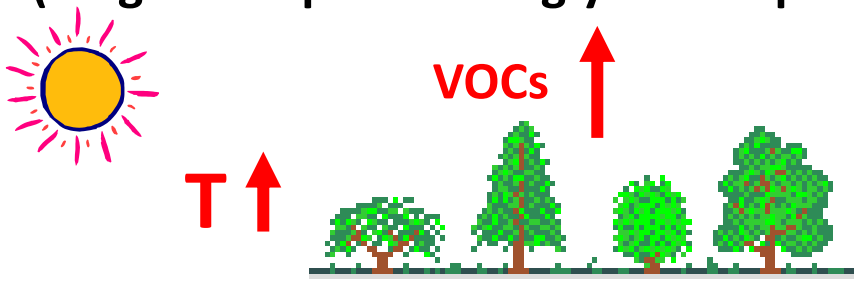
cyclonic ventilation of the eastern U.S.



(2) PAN chemistry, (3) biogenic emissions

(2) the amount of NO_x ($NO+NO_2$) sequestered by peroxyacetyl nitrate (PAN) decreases with increasing temperature

(3) Emissions (biogenic depend strongly on temperature)

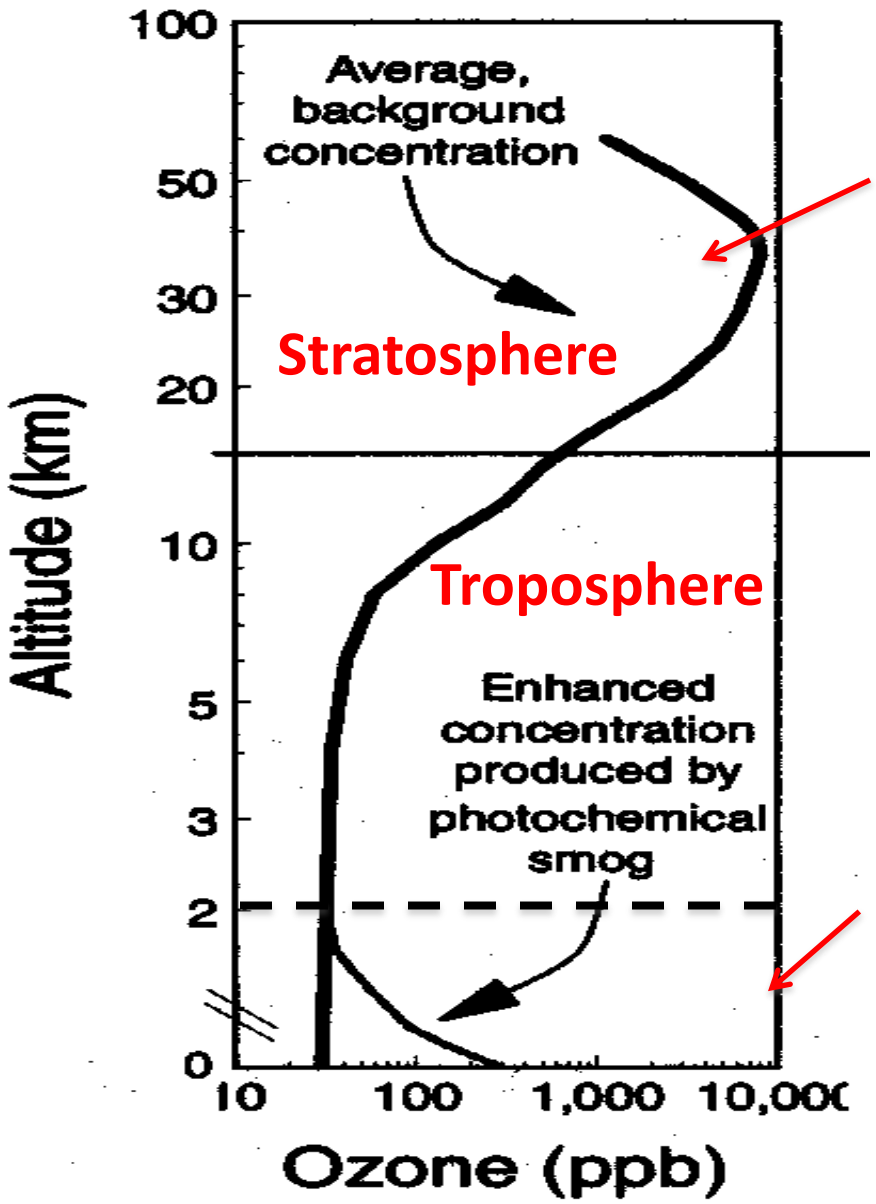


Why is O_3 relevant to climate?

Increasing…	Effect on O_3 concentrations:
Stagnation	↑
Temperature	↑
Wind speed	↓
Mixing depth	=
Cloud cover	↓
Humidity	=

[Jacob and Winner, 2009]

Ozone (O_3) in the atmosphere



Good (UV shield) 90% of column O_3 in our atmosphere exists here in the stratosphere

Bad (Smog) surface O_3 is toxic to both people and plants